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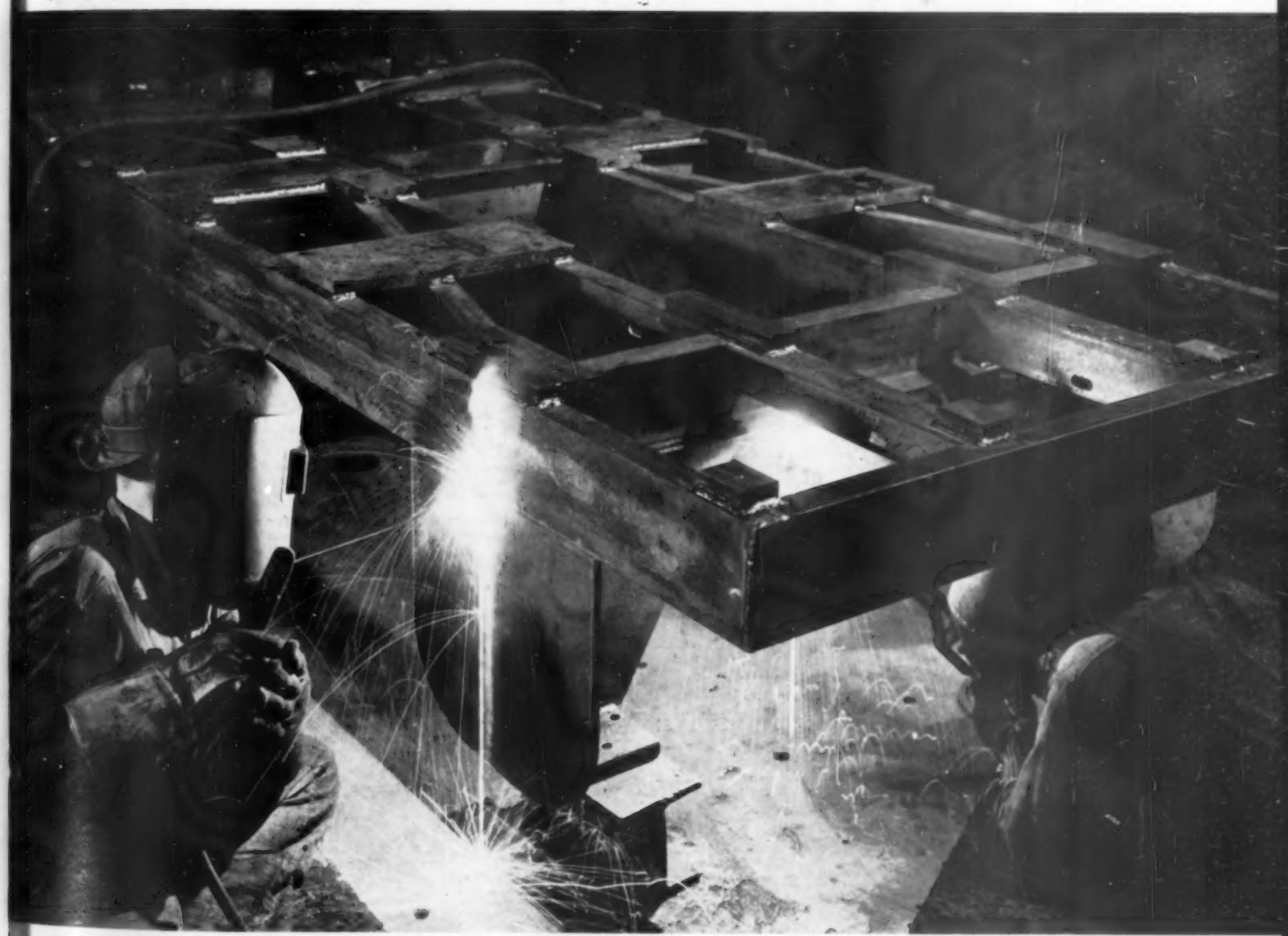

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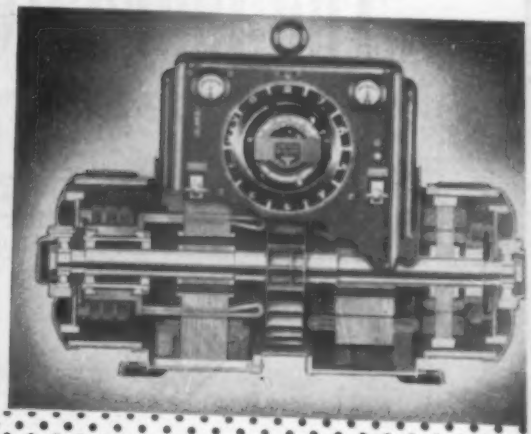

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Published for the Advancement of the Science and Art of Welding

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COVER

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CONTENTS

TECHNICAL PAPERS, ITEMS AND REPORTS

Stress and Strain in Plastic Flow, by Captain W. P. Roop, U.S.N. 799
Original Resistance Welder Design for Production of U. S. Navy 40-MM Ammunition Boxes, by F. M. Pence 824
Current Welding Literature 828
Codes for Arc and Gas Welding in Building Construction, by L. M. Dalcher 829
Variation in Quality of Spot Welds in Low-Carbon Steel Over a Range of Welding Variables, by J. J. Riley 833
Projection Welding Push Rod, by E. B. Rhodes 842
Limited-Input Arc Welders, by E. Steinert 844
Resistance-Seam-Welded Sacks Used as Hydraulic Presses, by R. T. Gillette 847
The Radiography of Spot Welds in Light Alloy and Ferrous Sheet Materials, by Robert C. McMaster and Frederick C. Lindvall 851
Causes and Prevention of Defects in Welding, by Frederick S. Dever 860

SOCIETY AND RELATED ACTIVITIES

Message from Our President 866
A.W.S. By-Law Amendments 866
Engineering Societies Council of New York Organized to Coordinate Program of Local Chapters of Engineering Societies 866
Southern Standard Building Code 866
New Headquarters for American Bureau of Shipping 870
A.S.M. Officers 870
INDEX TO ADVERTISERS 870
Lincoln Foundation Issues Brochure on $200,000 Design-for-Progress Program 872
Materials for Safety Wearing Apparel 874
Swiss Boiler Society 874
Swiss Acetylene Society 876
French-English Dictionary 876
Buying Guide 876
Mallory Expands 878
Resistance Welding Literature 878
Booklet Lists Articles on Spectrography 878
Floating Dry Dock Launched 878
Murex Electrodes 880
Newburn Made District Manager 880
"Low-Temperature" Welding Alloys 880
A. C. Brown Appointed District Manager 880
Nelson Announces British Isles Representation 882
All-Manganese Steel Welded Type Dippers 882
Dekker Promoted 882
Mullen Appointed Manager Ampco Resistance Welding Sales 882
A.-C. Bronze Electrode 882
Hard-Surfacing of Rolling Mill Skid Pipes 884
Jeep-Welder Combination Pays Dividends 884
Arc Welding and Flame Cutting at the Same Time 884
Radiant Heat 886
Welded Sewage Line 886
Sustaining Member 886
Employment Service Bulletin 886
A.S.T.E. Convention 886
New Products 888
Abstracts of Current Welding Patents, Prepared by V. L. Oldham 896
Section Activities 898
List of New Members 900
Baltimore Section Tour of U. S. Engineering Experiment Station Welding Laboratory, by Milton A. Hansen 900

WELDING RESEARCH SUPPLEMENT

Reduction of Residual Welding Stresses by the Use of Austenitic Electrode, by Finn Jonassen, J. L. Meriam and E. Paul DeGarmo .. 489-s
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The Fatigue Behavior in Reverse Bending of Welded Sheet Steel, by R. L'Hermite and D. Seferian ... 512-s
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Quantitative Measurement of the Cracking Tendency in Welds, by R. D. Stout, S. S. Tör, L. J. McGeady and G. E. Doan 522-s
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The Journal of The American Welding Society

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Stress and Strain in Plastic Flow*

By Captain W. P. Roop, U.S.N.

Introduction

FOR elastic action in steel a clear and comprehensive understanding is generally possessed by naval architects, and the set of concepts brought together in the theory of elastic action is fundamental in the design of ship structures.

That plastic deformation† continually occurs in the process of assembly of a steel hull is a fact known to every practical shipbuilder and some recognition has been given to plasticity also in courses of formal instruction. However, the idea that plastic deformation continues during the period of shakedown, or even in later service of a vessel, has not generally been brought into consideration.

The facts about plastic flow in steel and in other materials are still imperfectly known, and knowledge about plastic action is changing rapidly as new facts are uncovered. The concepts embodying this knowledge are immensely involved and complicated, and are by no means easily set down. The best account of them is found in Nadai's "Plasticity."[1]

It can be taken as a basic fact, however, that the capacity for plastic flow of the steel in the structure of a ship plays a most important part in the success of a ship in its efforts to keep afloat and in operation. The need for this capacity for plastic flow has at times not been recognized at all and has only rarely been considered in the course of design calculations for ship structure.

This report presents a point of view which contemplates systematic consideration of plastic action in steel not unlike that which has been developed in the course of many years for elastic action, and applied to ship design. In some sections it will quote experimental facts, but it does not pretend to give critical consideration to the great body of knowledge about plastic action at its present stage of development. It is intended to assist a person concerned with strength of ships in the digestion of the numerous data on special phases of plasticity now available and to show their relation to the design of ship structures.

At the same time it does not undertake to present in the ordinary sense a theory of plasticity. The theory that will command universal acceptance is not yet formulated. The report undertakes to supply naval architects only with some useful concepts of plastic action, emphasizing principally the points at which the treatment of *plastic* action differs from the familiar treatment of *elastic* action, and with some ideas of practical value for use in the meantime.

In some respects the plastic theory, when it becomes available, may be found easier to master than the elastic theory. Thus, in plastic theory, the invariant density of the metal makes the value of Poisson's ratio always equal to 0.5. However, plastic theory has no Hooke's Law, and the idea of plastic stress therefore seems difficult to grasp to a person imbued with the idea that "stress is proportional to strain." Or possibly it is even worse than that because in certain cases, a spurious Hooke's Law makes its appearance. In those cases, deflection, at least approximately, is directly proportional to load even in the plastic range, though in a different ratio and for a wholly different reason than in the elastic range.

It is the intent of this report to resolve the resulting confusion by proceeding by easy stages from the simple case of tension in a wire toward the intricacies of triaxial action and localized distribution.

This will lead eventually to the point of explaining the theory of "octahedral stress and strain" for some simple cases of extended structures. Nonuniformity of plastic action is another matter; the additional complications that arise, as in any practical case, when stress and strain distributions are not uniform, mostly lie beyond the limits of the present undertaking. The examples chosen for illustration are therefore simplified. This is done because the real difficulties arise from our unfamiliarity with the simple facts about plastic action. Once these are clearly understood, the problems of distribution of plastic effects in an extended structure should yield their solutions to well-tried methods of mathematical procedure like those which have been used so successfully in the elastic range.

1—Uniaxial Stress and Strain

Elementary stress and strain as they exist in the uniaxial case of a wire in tension are familiar concepts which do not need revision. They are well presented in many easily accessible books, notably in *Elements of Strength of Materials* by Timoshenko and MacCullough.[2]

Stress

When a force acts on an imaginary interior surface, as in Fig. 1, the force per unit area of the surface is called stress. If the force makes a right angle with the surface, the symbol σ is used for the stress, and if it acts parallel to the surface, the symbol is τ. Ordinarily, both normal and the tangential components of force will be present. An interior surface may be formed by an imaginary cut made at any given place in a piece of steel, and this cut may be oriented in any way desired; if the cut is turned so as to make τ zero the normal stress σ remains alone; the latter is then called a principal stress and is distinguished by a numerical subscript, thus: σ_1.

In a wire under uniform tension the geometrical axis

* Opinions expressed are those of the author and not of the Navy Department.

† The terms "plastic deformation" and "plastic flow" are here used interchangeably, although the first is sometimes reserved for static action.

of the wire is an axis of principal stress, and the tangential component of stress on a right transverse section is zero. Likewise on a longitudinal cut in the wire, as in Fig. 2, the tangential component of stress is again zero, and in this case the normal component is also zero. It is a familiar and plausible result of analysis that the tangential component of stress, τ, which thus has zero value on both the axial and longitudinal cuts, will attain its maximum value on a cut midway between, at 45° with the axes. This tangential component of stress is called shear stress.

Strain

A little less simple is elementary strain. It refers basically to change in length per unit length, and thus, like angle, has zero dimension.* But from the very beginning of the analysis special attention must be given to the transverse components of strain.

A wire of unstrained length L_0 is stretched out to a greater length L, as in Fig. 3. By the ordinary definition, strain is then $= (L - L_0)/L_0$.

Now it is a fact that the resistance of steel to a change in volume is very much greater than to a change in shape. In the elastic range volume increases with strain; thus transverse contraction is less than enough to make up

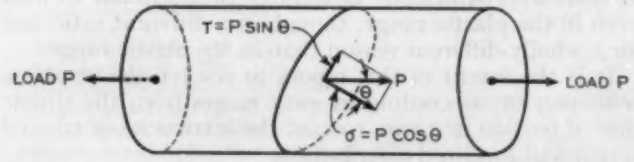


Fig. 1—Components of Stress in a Wire in Simple Tension

The force transmitted through an oblique section of the wire may be resolved into normal and tangential components.

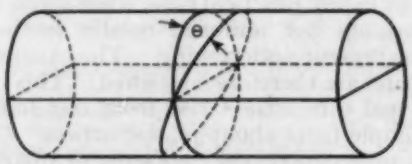


Fig. 2—Axial and Transverse Sections of a Wire

When θ is zero, τ is zero and the normal stress is σ_1. In the case of the longitudinal section θ is $\pi/2$ and both τ and σ are zero.

for the axial elongation of a wire in tension; its ratio to the axial elongation, known as Poisson's ratio, has a value of about 0.3. However, as soon as plastic flow begins, the further change in volume is very small. Thus if the cylindrical wire stretches out plastically into a new cylinder of greater length and smaller section, as in Fig. 3, the new volume AL is closely equal to the original volume A_0L_0. If the length increases by the fraction ϵ, each of the transverse dimensions diminishes by a fraction $\epsilon/2$. The value of Poisson's ratio in plastic flow is therefore 0.5.

It is thus a fact that a stress consisting of a single component, like that in a wire in uniform tension, causes strains in directions in which there is no stress. It is generally not possible to split strain into components, each dependent only on the corresponding component of stress. The relation between stress and strain is more complex than that.

Stress-Strain Relation

In the case of a wire in simple tension, however, there is a direct relation between axial stress and axial strain. Since this case is free from the geometrical complexities

* Since length is involved to the zero power.

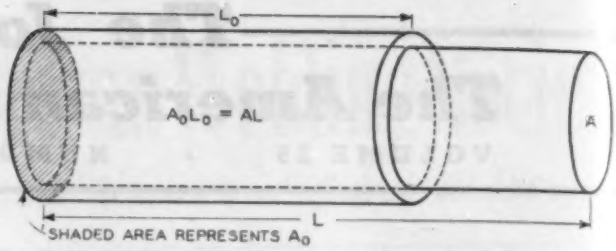


Fig. 3—Diagram Showing Plastic Elongation of a Wire

of more elaborate stress patterns, it forms a suitable medium for dealing in an elementary way with complexities of another sort, namely, those of the conditions attending plastic flow. The relation is to be explored in three different ranges:

(*a*) Up to the elastic limit, stress equals strain times the elastic constant known as Young's Modulus. This corresponds to the left-hand linear part of the diagram in Fig. 4.

(*b*) Beyond the elastic limit, the relation changes its character altogether. As an approximation, it is sometimes assumed that an increase in strain beyond the yield point is accomplished by no further increase in stress and that flow is resisted only by the yield stress. According to this, the application of a load exceeding the yield value would result in accelerated flow.

In general, however, an increase in load beyond the yield value causes a certain elongation, after which the elongation ceases; to obtain more elongation, more load is needed. This means that beyond a certain point the load-elongation curve rises as shown in Fig. 4.

Putting the matter in another way, it may be said that the plastic straining beyond the yield point increases the capacity of the metal for resistance to further plastic flow. This increased "strength" is an aspect of increase in hardness after plastic strain, known as strain hardening.*

This phenomenon has the peculiar characteristic that it is irreversible except by heat treatment; upon release of the load in the strain-hardening range, the metal shows elastic behavior within the limit of stress previously attained, which now becomes the new yield point. These details and the trend of stress as a function of strain are suggested in Fig. 5.

* Time also plays a part in these phenomena, through such effects as aging, creep and change of stress caused by change of strain rate; for a simplified introduction, these complications are ignored for the present.

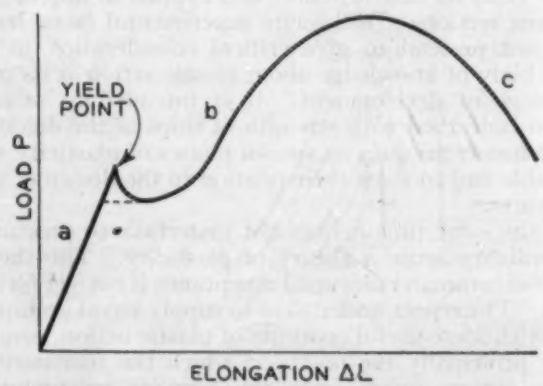


Fig. 4—Schematic Load-Elongation Diagram for Steel

In the range *a*, the action is elastic and linear. Entering the range *b*, the load may overshoot and then diminish as shown, or it may follow the dotted horizontal line. In either case an increase is presently needed to cause more elongation. Entry into the range *c*, where necking begins, marks the point of maximum load. In ship steel range *a* is much narrower than range *b*. The diagram is schematic only. See also Fig. 5.

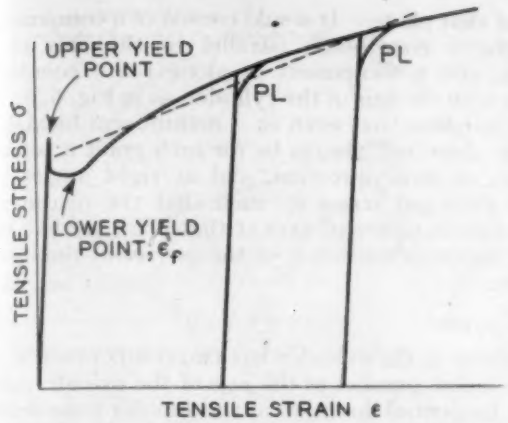


Fig. 5—Stress-Strain Diagram Showing the Effect of Strain Hardening

At initial loading the stress rises to a peak or "upper yield point" from which it may drop to a "lower yield point" before again rising. Release of load permits recovery in the elastic mode. After each increment of plastic flow the limit separating elastic from plastic action is raised, as at the points marked *PL*. When plotted as true stress against true strain, this curve shows no maximum, but continues to rise until ended by rupture. It is this increase of the plastic stress limit caused by plastic deformation which is called "strain hardening."

(*c*) The increase of load necessary to cause plastic strain continues as just described only up to a certain point, beyond which necking sets in; the stress loses its uniform distribution and runs into concentrations in the neck, accompanied by transverse components of stress in the tapering segments. If elongation is maintained at a constant time rate the load falls off, though in the neck the stress continues to increase. If the load is maintained, the stress in the neck increases faster and faster, to the point of early rupture.

In materials testing practice the peak load value at which plastic flow begins is known as the upper yield point. Once started, plastic flow then continues without an increase or possibly even with a decrease of load, as indicated by the "drop of the beam." In this way it becomes necessary to distinguish an upper and a lower yield point as shown in Fig. 5. Further increase of stress occurs only after strain has increased, as at the point marked ϵ_f.

True Stress and Natural Strain

As elongation increases beyond the elastic limit, a point is soon reached at which the loss of area in the specimen must be taken into account. Not only must the load be divided by the reduced area in figuring stress, but the corresponding strain values are also affected. Strain will be differently evaluated when the elongation is divided by the original length or by the final length, or by some intermediate or average value. The ordinary conventional practice is to divide the elongation by the original length. If, as is sometimes done, strain is expressed rather in terms of reduction in area, then it would be written $(A_0 - A)/A_0$. Since $AL = A_0L_0$ it will be seen that

$$\frac{A_0 - A}{A_0} = \frac{L - L_0}{L}$$

Strain so calculated is thus equal to the elongation divided by the final length, and it has a smaller value than if elongation were divided by the original length.[3]

Special importance attaches to the case in which each small increment of strain is referred to an average length during the strain. Thus $\Delta\epsilon = (\Delta L/L)$, and then the whole strain from the unstrained condition $L = L_0$ to a final value $L = L$ is

$$|\epsilon|_{L_0}^{L} = \int_{L_0}^{L} \frac{dL}{L}$$

This results in the expression*

$$\epsilon = \ln \frac{L}{L_0}$$

for strain; strain as so defined is called natural strain. In view of the relation $AL = A_0L_0$ it is equally true that $\epsilon = \ln (A_0/A)$, and in measurements on a tensile specimen this latter relation is generally the more useful of the two.

The correction which must be made to reduce ordinary stress to true stress consists in multiplying by A_0/A; this factor may be written

$$\frac{\text{true stress}}{\text{ordinary stress}} = \frac{A_0}{A} = e^{\epsilon} \doteq 1 + \epsilon$$

No special symbols are needed to distinguish the ordinary from the true values. Wherever the difference is significant the true values are to be used.

The difference between the ordinary and the logarithmic strains in the range of uniform action, below the necking point, is not very great; thus when ordinary strain, expressed by $(L - L_0)/L_0$, is 20%, the natural strain expressed by $\ln (L/L_0)$ is 18.2%.

Plotting the true stress against strain gives, for a point in a wire, a curve for the plastic region as shown in Fig. 5, to which a first approximation is a sloping straight line with an intercept on the stress axis equal to a value lying between the upper and the lower yield points, as shown by the broken line in that figure.

The principal departures from such an approximation occur in the neighborhood of the yield point. If the upper yield point, as well as the elastic action preceding it, be disregarded, a still better approximation to an actual stress-strain curve is given by the expression $\sigma = \text{const.} \times \epsilon^q$. In a series of carefully measured specimens[4] of medium steel, q was closely equal to 0.25 and the constant was about 112 when σ was expressed in kips per square inch.

Energy

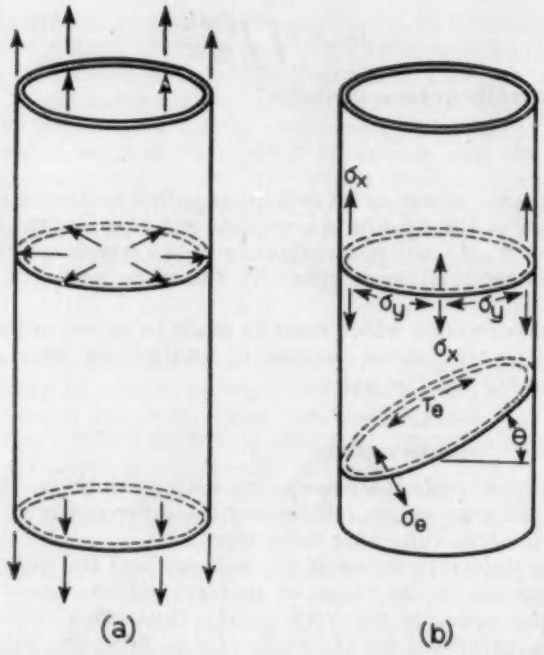
The total energy absorbed by plastic flow in any stretched wire is the product of its elongation and the average tension. If the plastic tension were independent of elongation, that constant value of plastic tension would be the average. Such a result is obtained if the strain hardening increases the plastic stress just enough to offset exactly the loss of section area. The strain hardening may, however, depart from this amount in either direction.

For purposes of dealing with energy in the strain-hardening range it may be more convenient to consider ordinary stress and strain.

If the plastic flow in the wire is uniformly distributed over the whole length and section of the wire, the energy per unit volume may be found by dividing the product of the average load and the elongation by the volume, which is the product of the initial area and the initial length. But load divided by initial area is ordinary stress and elongation divided by initial length is ordinary strain. The energy absorbed per unit volume up to the point at which necking begins is thus given by the area under the ordinary stress-strain curve and the energy at a series of ordinary strains may be plotted by progressive integration of the ordinary load-elongation record as found by a standard tensile test.

The total energy absorbed after necking begins is relatively small if the volume of metal participating in the necking action is a small part of the whole. The

* The symbol "ln" denotes natural logarithm.



(a) Representation of loads. (b) Representation of stresses.

Fig. 6—Diagram of Thin-Walled Tube Loaded to Produce Uniform Biaxial Stress with Variable Component Ratio

The longitudinal component of stress is σ_x, and the peripheral component is σ_y.

load elongation curve still gives the energy absorbed in the whole specimen, but the energy absorbed per unit volume now varies from one point to another; at the constriction in the neck, where rupture eventually occurs, the strain may rise to many times the highest values attained in the range of uniform elongation, with a like result for the local value of energy per unit volume.

This local value of energy per unit volume depends on the value in the neck of $\sigma = \frac{P}{A_0}\cdot\frac{A_0}{A}$. There as everywhere the increment of natural strain is

$$\Delta\epsilon = \frac{A}{A_0}\,\frac{\Delta L}{L_0}$$

if A and L_0 refer to local values. The energy

$$u = \int \sigma d\epsilon = \frac{1}{A_0 L_0}\int P dL$$

As L_0 is taken shorter and shorter the local energy rises to higher and higher values.

2—Biaxial Stress and Strain

Coming now to combined stress and strain, in which these occur simultaneously in more than one direction, consider a thin-walled cylindrical tube loaded by a combination of axial tension and internal fluid pressure. In a specimen of this kind, a nearly uniform distribution of biaxial stress and strain is achieved. The axial tension, uniformly distributed over an annular right section, as in Fig. 6 (*a*), gives an axial component of stress which in the case of the wire was the only component. The internal pressure gives a nearly uniform peripheral or hoop tension, and on a longitudinal or meridional section, this gives a normal stress at right angles to the axis of the tube.

If the cylinder were cut longitudinally and flattened out to a plane, as is done in the manufacture of window glass, the condition of stress would be the same at all points of that plane. It would consist of a component σ_x along the x coordinate, parallel to the axis of the cylinder, and a component σ_y along the y coordinate, transverse to the axis of the cylinder, as in Fig. 6 (*b*).

It so happens that even in a nonuniform biaxial distribution there will always be for each point a principal stress σ_1, in some direction, and at right angles to it another principal stress σ_2, such that the relations referred to those principal axes at that point are like those that prevail over the whole of the surface of the tubular specimen.

Biaxial Stress

The stress in the cylinder has two components, σ_x and σ_y; σ_x is taken parallel to the axis of the cylinder and σ_y lies in a tangential direction in the annular cross section. The stress σ_x equals the axial load divided by the area of the annulus, and the stress σ_y equals the internal pressure times the ratio of radius to wall thickness, by the usual boiler formula. These are the principal stresses, the normal stresses in terms of which other details with respect to the state of stress are most easily expressed.* The radial component, σ_z, is taken to be zero.

A subscript attached to the symbol σ or τ used to designate stress will always indicate a definite component of stress. But usages differ in the choice of subscript to be used for given components. Commonly the digits 1, 2 and 3 are used for the maximum, intermediate and minimum components (tension positive) regardless of orientation in the metal. That usage must be distinguished from the one now in use here: σ_x is axial stress in the tube, σ_y peripheral and σ_z radial, regardless of magnitude.

If a diagonal plane intersects the cylinder, as shown in Fig. 6 (*b*), so as to form a plane figure bounded by two concentric ellipses (an elliptical annulus) an element of the area of this annulus is acted on by force whose resultant is made up of the two principal component stresses σ_x and σ_y. The stress on such an oblique section of the cylinder may also be resolved into a normal component σ_θ and a tangential component τ_θ. Here again, as in the wire, where $\sigma_y = \sigma_z = 0$, τ is still zero when the section is cut transversely to the axis of the cylinder and also when it is cut longitudinally or parallel to the axis. It has a maximum value where the section is cut at 45°. This is true even though σ_y and σ_z are not zero.

When both stress components σ_x and σ_y act together, use is made of a simple geometrical construction known as the Mohr stress circle to find the stress on the oblique section. A detailed explanation of this construction is not needed here, since it is found in the textbooks on the strength of materials, but an example is given in Fig. 7. The construction is as valid in connection with plastic as with elastic action, since the forces are affected only by loads and by geometrical relationships and not by the processes by which the geometrical form was attained.

In particular it will be seen how the Mohr construction shows that the tangential stress on any section, τ has a maximum value at an angle midway between the principal axes, and that the value of this maximum is

$$\tau_{xy} = \frac{\sigma_x - \sigma_y}{2}$$

* There is no completely satisfactory term to denote the condition which exists at a single point of stressed body, the state of stress in all its aspects; the word stress has here been used to refer simply to "force per unit area." At a given point a variety of such forces and stresses act, depending on the choice of the imaginary section cut in the body. The word "tensor" has been devised by mathematicians to denote a quantity of this nature, which requires several numerical values for its exact specification. A familiar example of a tensor is a vector, which in ordinary language is simply a quantity which has both magnitude and direction. This concept has been so broadened by mathematicians as to give the idea that the word "tensor" should be reserved for more intricate examples like those treated in "tensor analysis." In lack of a better usage, however, the whole combination of aspects of stress at a point will here be referred to as a simple tensor. A tensor is described in the *Mathematics Dictionary* by Glenn James as follows: "An abstract object having a definitely specified system of components in every coordinate system under consideration and which can be considered to be defined by the totality of its components in the various coordinate systems."

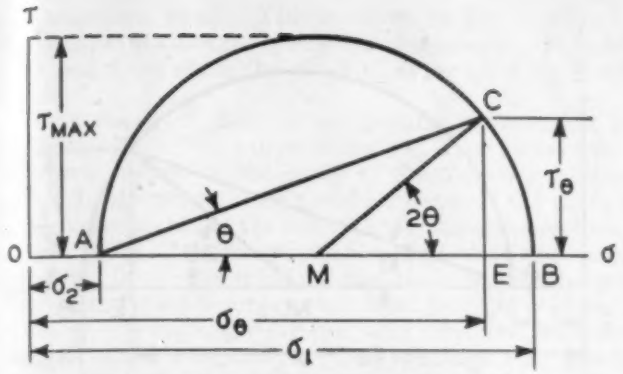


Fig. 7—Mohr's Stress Circle for Plane Stress

The circle is drawn by laying off the greater principal stress, σ_1, as OB, and the smaller, σ_2, as OA, so that $OM = {}^1/_2(OA + OB)$; M is the center and $AM = MB$ the radius. The angle of obliquity, θ, as in Figs. 1, 2 and 6 (*b*), is laid off at AC, and the angle CMB equals 2θ. Drop CE perpendicular to OB. The normal stress on the oblique section is σ_θ, and it is measured by OE. The tangential stress on the oblique section is τ_θ and it is measured by EC. Its maximum value occurs when $\theta = \pi/4$ and equals $(\sigma_1 - \sigma_2)/2$. When axial tension exceeds hoop tension, $\sigma_1 = \sigma_x$ and $\sigma_2 = \sigma_y$; when hoop tension exceeds axial tension, $\sigma_1 = \sigma_y$ and $\sigma_2 = \sigma_x$.

The sign is commonly ignored; it is partly for convenience in this connection that calculations are made in terms of σ_1, σ_2, σ_3, rather than σ_x, σ_y, σ_z.

In Fig. 8 a series of Mohr circles of stress have been plotted to cover the range of possible values of the ratio $n = \sigma_y/\sigma_x$ of the two components of principal stress that can be produced in a thin tubular specimen. In Fig. 8 (*a*) there is no internal pressure, but only axial tension, and $n = 0$. The ratio n is equal to unity in Fig. 8 (*b*); this condition may be produced in a hollow, thin-walled, uniform sphere under internal pressure, or at the center of a thin circular diaphragm under fluid pressure, or in a circular drumhead under uniform radial tension at the rim; the same value of the ratio can be obtained in the tube by combining fluid pressure with axial tension in the right proportions. This case is sometimes indicated specifically by the phrase "biaxial tension" to designate two equal principal tensile stress components. Figure 8 (*c*) shows how, if the ends of the tube are closed and the internal pressure acts alike on ends and walls, $n = 2$. Finally the value $n = \infty$, as shown in Fig. 8 (*d*), represents the case of radial pressure alone, as might be obtained by internal hydrostatic action in an open-ended tube, closed by plugs or pistons supported separately to resist the axial thrust of the pressure in the tube.

The cases shown in Fig. 8 refer only to combinations of axial *tension* with hoop *tension* as produced by *internal* pressure. The introduction of axial compressive action and of external pressure would widen the range of cases to be considered, but these are left aside for the present.

Biaxial Strain

Again, as in the uniaxial case, strain requires for its full discussion more elaborate preparation than stress. The whole present treatment is limited to relatively small strains, such as occur in uniform actions like that in a wire below the necking point. This, however, includes a wide range of action beyond the yield point, as from a strain of 0.1% to, say, 10%.*

Cylindrical Tube Under Combined Load.—When the cylindrical tube is elongated by axial tension alone, it loses both thickness and diameter. Under internal pressure, on the other hand, the tube increases in diameter without change in length, and again loses thickness, as will be explained shortly.

If the cylinder under axial tension only were slotted longitudinally to divide it into a number of simple rods of roughly square section, each of these rods, as it contracted in the radial direction, that is, in thickness, would also contract equally in the peripheral direction. The result of this latter contraction would be to open up the slots between the rods. But if the slots had not been cut a contraction in diameter would be necessary. It is in fact observed in the plastic flow of a tube under axial tension that the fractional changes in diameter and in thickness are approximately equal.

A similar artifice, of dividing the tube into circumferential or transverse elements, indicates that under hoop tension alone, each element would enlarge in diameter and would become thinner and shorter. If all the elements were then permitted to pull together, a shortening of the tube would occur, and the fractional amount of this contraction in length would equal the fractional reduction in thickness.

Now if axial and hoop tensile deformations were to be combined in different ratios, the two sets of effects would

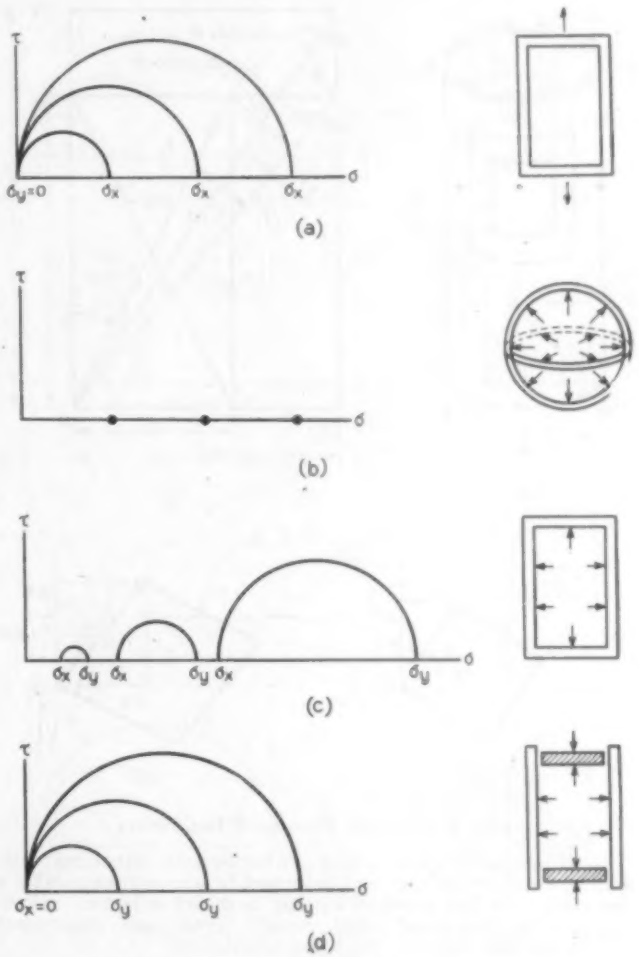


Fig. 8—Various Ratios of Principal Stress Exhibited by Mohr Circles

(*a*) Cylinder under pure axial tension, $n = 0$. (*b*) Sphere under internal pressure, $n = 1$. (*c*) Closed cylinder under internal pressure, $n = 2$. (*d*) Open-ended cylinder under internal pressure, $n = \infty$; the ends are closed by loose plugs supported externally.

In each case three successive intensities of stress are shown. n is taken here to be the ratio of the peripheral to the longitudinal component, regardless of which is larger.

* Much higher values of uniform strain have been obtained in special circumstances. In such cases any theory which assumes strain to be infinitesimal has only qualitative validity. In particular the tacit assumption that axes of stress and of strain coincide in direction may depart widely from the truth. The end result may also depend on the sequence of straining operations. The theoretical treatment of finite strains lies far beyond the limits of this report, and errors caused by assuming strain to be infinitesimal, though unknown, must for the present be accepted.

naturally be superposed* so as to produce a variety of results. Thus, for example, if just enough internal pressure were applied to prevent loss of diameter in a tensile test, this would be equivalent to an axial tensile elongation followed by enough hoop expansion to restore the diameter to its original value. This expansion would naturally result in loss of length; the net result of the two operations would be a residual increase of length smaller than would be caused by axial tension alone.

It happens that this could be accomplished exactly by the amount of internal pressure necessary to make hoop stress half the axial value, i.e., n equal one-half, but it is clear that similar stresses would generally be caused by any constraints operating to prevent the reduction in diameter which would normally go with the axial strain. Thus filling the cylinder with incompressible material and pulling axially on it would set up hoop stresses. Similarly, tension in a ship plate prevented from transverse contraction gives rise to transverse stresses, and so to reduced elongation in the direction of the external or applied tension.

Again, it happens that if axial tension were applied in the right amount to make n equal 2, the axial contraction caused by the hoop tension will just offset the axial elongation caused by the axial tension so that change in length is zero. This is the condition shown in Fig. 8 (*c*).

* The principle of superposition, however, has no general and exact application under the nonlinear conditions of plastic flow.

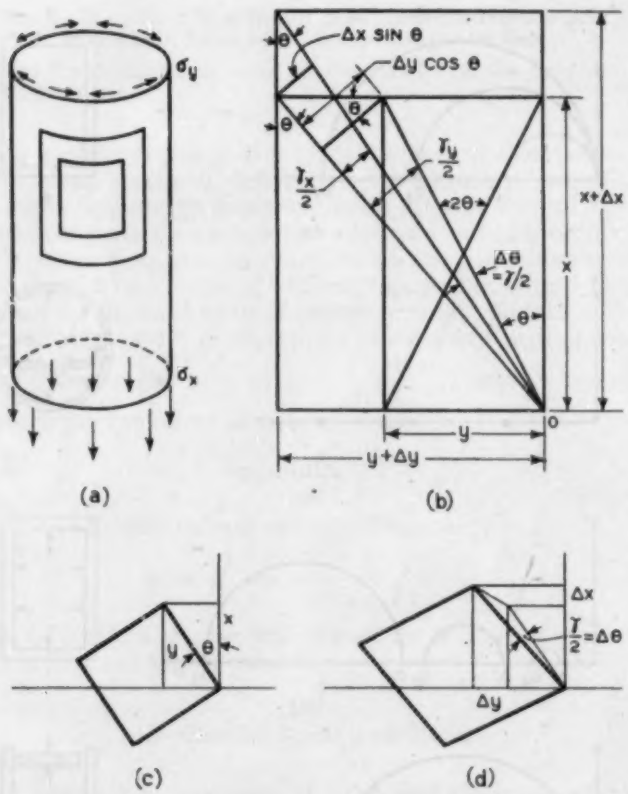


Fig. 9—Diagram Showing Biaxial Strain

(*a*) Schematic diagram showing a rectangular panel cut in the wall of a hollow cylinder and deformed by elongations parallel to the sides. (*b*) The panel of Fig. (*a*) is shown enlarged, and for convenience the lower right corners have been superposed. (*c*) The diagonal square. (*d*) Shear deformation.

x and y are the sides of a rectangular panel cut parallel to the longitudinal and transverse axes. Each of the diagonals makes an angle θ with x, so that the angle between them is 2θ. When the cylinder is strained by loading, x, y and θ change to $x + \Delta x$, $y + \Delta y$ and $\theta + \Delta\theta$. Comparison with Fig. 10 shows that strain is a tensor analogous with the stress tensor shown in Fig. 7.

The nature of shear deformation is illustrated by cutting from the tube wall a square turned at an angle θ to the x-axis, as in (*c*). The strain operation transforms the square into a diamond, as in (*d*), where direction shifts have occurred in the sides though not in the diagonals.

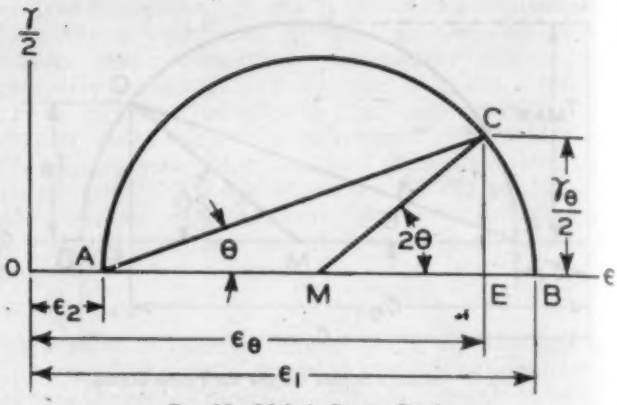


Fig. 10—Mohr's Strain Circle

The circle is constructed in the same manner as the stress circle of Fig. 7, but the quantities are purely geometrical and the properties of Fig. 10 may be demonstrated by reference to Fig. 9 if the linear strains ϵ_1 and ϵ_2 are identified with $\Delta x/x$ and $\Delta y/y$ and the shear strain γ is identified with *twice* $\Delta\theta$, or $\Delta(2\theta)$. Note that the ordinate as plotted is half the shear strain. ϵ_1 is either ϵ_x or ϵ_y, whichever is larger, and ϵ_2 is the smaller of the two.

Shear Strain

Shear strain plays an important part in plastic deformation; it will therefore be given some additional attention in detail. Shear is only one aspect of general deformation or strain; it has a definite relation to the more familiar concepts of tensile strain, and this relation will now be examined in a purely geometrical way without reference to the question as to what may cause the strain.

Consider a rectangle which forms part of a biaxially strained plate, such as may be marked off from the wall of the biaxially loaded tube, as in Fig. 9. The sides of the rectangle are parallel to the principal axes; the side x is parallel to the axis of the tube, and the side y is perpendicular to it.

The point x, y is now moved to the point $x + \Delta x$, $y + \Delta y$. The ordinary tensile strains parallel to the principal axes are $\epsilon_x = \dfrac{\Delta x}{x}$ and $\epsilon_y = \dfrac{\Delta y}{y}$. By the geometry of Fig. 9, if $\gamma/2$ is the increment of θ,

$$\left(\frac{\gamma}{2}\right)_x = -\frac{\Delta x \sin\theta}{\sqrt{x^2 + y^2}}$$

$$\left(\frac{\gamma}{2}\right)_y = +\frac{\Delta y \cos\theta}{\sqrt{x^2 + y^2}}$$

But the length of the diagonal

$$\sqrt{x^2 + y^2} = \frac{y}{\sin\theta} = \frac{x}{\cos\theta}$$

By combining these relationships

$$\frac{\gamma}{2} = \frac{\gamma_x}{2} + \frac{\gamma_y}{2} = \left(\frac{dy}{y} - \frac{dx}{x}\right)\sin\theta\cos\theta$$

So that $\gamma = (\epsilon_y - \epsilon_x)\sin 2\theta$. It is this angle γ, the increment of 2θ, which is identified with shear strain.

In view of the uniformity of the stress distribution it is not necessary to think of the rectangle of Fig. 9 as infinitesimal. However, there are restrictions with respect to the magnitude of the strain; large strains such as occur in the necking range are beyond the limits that can be treated by the present analysis.

On the principal axes x and y the strains always consist of simple elongations, but on intermediate orientations the diagonal is shifted in direction unless the two princi-

pal strains are equal. This is shown in Fig. 9 (*b*). A deformation of this type is denoted *shear* strain. Figures 9 (*c*) and 9 (*d*) show the effect of shear on a diagonal square.

The concept of shear as an angular deformation is familiar enough. In a deck of cards it is the ratio of the transverse sliding of the cards to the thickness of the pack. In the present case the shear strain is the change in the angle 2θ, where the angle θ is as illustrated in Figs. 1, 2 and 6 (*b*). Its dimensions, like those of linear strain, are zero. In the two principal directions, represented by x and y, the plate is simply stretched; but the diagonals of the $x - y$ rectangle are not only stretched, but are changed in direction as well. It is the angle γ by which this change is measured which is accepted as the measure of shearing strain.

The formula for strain justifies a graphic construction similar to that shown for stress in Fig. 7. Details of the Mohr strain circle are given in Fig. 10. It shows that the shear strain, like the shear stress, is a maximum at $\theta = 45°$. This maximum value itself is often designated by the same name, shear strain, and by the symbol $\gamma = \epsilon_y - \epsilon_z$.

The sign of the shear strain γ is of no importance for present purposes; it is therefore taken only in terms of its absolute value, as $\epsilon_y - \epsilon_z$ or $\epsilon_z - \epsilon_y$, depending on whether ϵ_y or ϵ_z is greater. These strain relations, as exhibited graphically in Fig. 10 are seen to be closely analogous to those shown by the Mohr stress circle, Fig. 7.

The maximum shear, both in stress and strain, is found at either of the sections midway between the two principal axes, at which $\theta = 45°$. These are therefore sometimes called the principal axes of shear. However, this expression is somewhat misleading, since the specification of the so-called principal shear is not sufficient for evaluating all the other terms of the tensor.* Referring to the Mohr circles it will be seen that the shear maximum establishes the size of the circle, but not its position with respect to the origin.

It is seen that the strain can be regarded as a tensor, with components on a section at the angle θ designed as ϵ_θ and γ_θ in a way quite analogous to the representation of the corresponding components of the stress tensor as shown in Fig. 7.

It is a special and noteworthy fact that whereas the radius of the Mohr circle of *stress* represents the shear *stress* maximum directly, the radius of the *strain* circle represents only half of the maximum shear *strain*. In Fig. 10 *CE* must be doubled to obtain the value of shear strain. This is a conventional but almost universal usage.

A series of cases in which hoop strain and axial strain are combined in various proportions are exhibited in Fig. 11, with the corresponding strain circles. The various cases are accompanied by diagrams illustrating the corresponding deformations of a unit segment of metal initially square. They apply to assigned values of the ratio of the principal strains; for which the symbol m is adopted. These strain ratios must not be confused with the ratios of the principal stresses, which are denoted by the symbol n. The diagrams at the right margin of Fig. 11 illustrate the deformations of a square subjected to varying ratios of the two principal strains.

Stress-Strain Relation

The discussion of biaxial stress and strain up to this point has served only to define the terms in their physical and geometrical aspects; but the nature of the plastic strain which accompanies a given applied stress is a matter to be observed, not simply defined. Observation of the strain occurring under the application of given values of the two principal components of stress, σ_x and σ_y, has been undertaken in a series of careful tests, the results of which have been separately reported.[4] The general results of these tests is to demonstrate that the results of a single tensile test may be made applicable to all biaxial conditions through the use of the theory of "octahedral stress and strain," which is discussed in Parts 4 and 6 of this report.

3—Triaxial Stress and Strain

It is usual, in the tubular specimen loaded with an internal pressure, to ignore the radial component of stress. At the outer wall of the tube it equals atmospheric pressure, and at the inner wall, the internal fluid pressure. The hoop stress exceeds this in the ratio of the tube radius to the wall thickness. In relevant cases this latter ratio would largely exceed 10 to 1, as it is of the order of the width-thickness ratio in ship plating.

Strain in thickness, however, is not at all negligible; on the contrary this component of strain will usually exceed the others in our cases.

The only safe way of proceeding is therefore to take

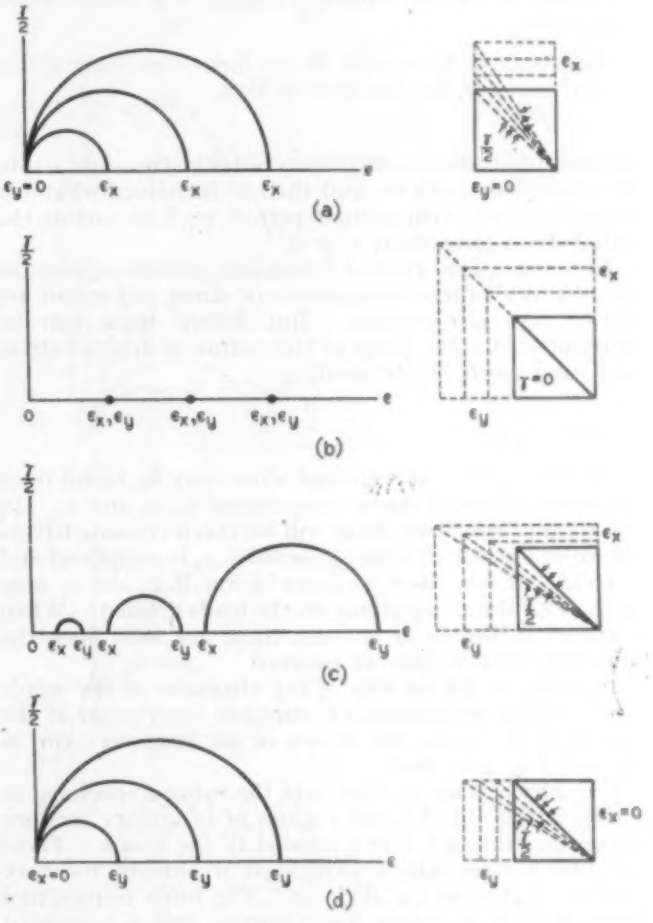


Fig. 11—Various Ratios of Principal Strains Exhibited by Mohr Circles

(*a*) Strain in the axial direction only, $m = 0$. (*b*) Axial and hoop strains equal, $m = 1$, shear strain zero. (*c*) Hoop strain double the axial value, $m = 2$. (d) Axial strain zero, $m = \infty$.

The geometrical strains are shown on the right in each case, according to the scheme used in Fig. 9. Note especially that the cases shown are for assigned values, not of the stress ratio $n = \frac{\sigma_y}{\sigma_x}$, but of the strain ratio $m = \frac{\epsilon_y}{\epsilon_x}$. In each diagram three successive levels of strain are shown.

* See the footnote on page 802.

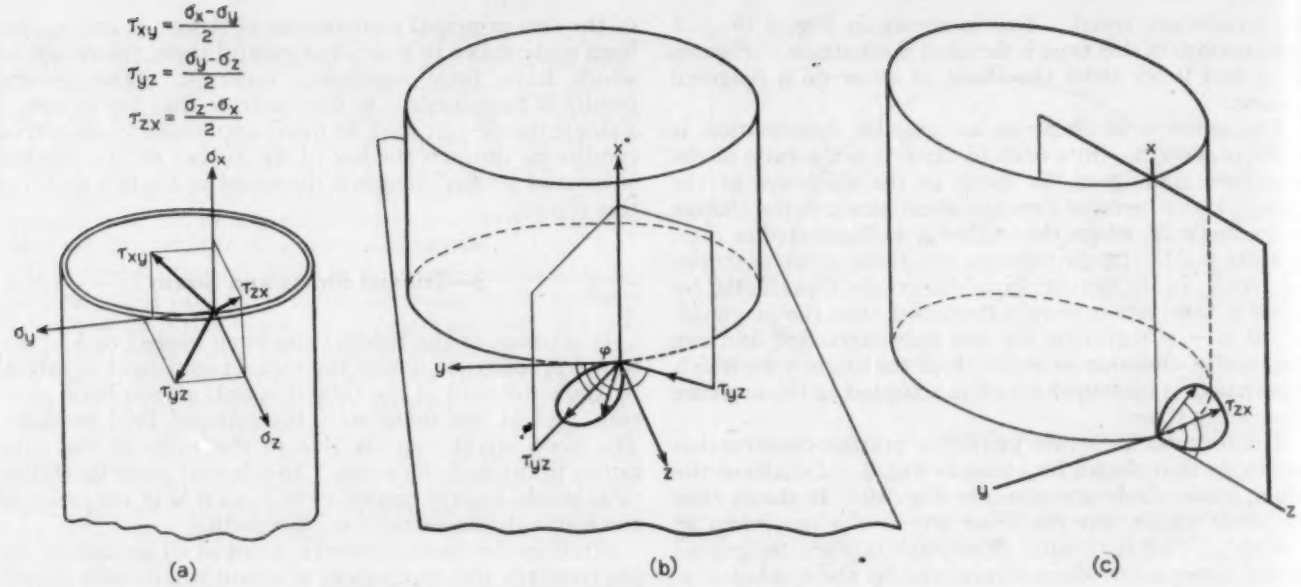


Fig. 12—Triaxial Components of Stress in the Hollow Cylinder

(*a*) Coordinate axes and nomenclature of the stress components. (*b*) Shear stress on oblique sections of the y-z plane, at various values of the angle φ, measured about the x-axis. (*c*) Shear stress on oblique sections of the z-x plane.

Reference is now made to the three-dimensional Cartesian coordinates, x in the axial direction, y in the peripheral and z in the radial direction.

account of all three components of both stress and strain in a complete analysis, and then to introduce whatever simplifications circumstances permit, such as putting the radial stress component $\sigma_z = 0$.

Important new general conditions become applicable as soon as all three components of stress and strain are drawn into the account. But before these can be introduced, a clear grasp of the nature of triaxial stress and strain must be obtained.

Triaxial Stress

All the features of a triaxial stress may be found from the three principal stress components σ_x, σ_y and σ_z. In the tubular specimen these will be taken consistently as shown in Fig. 12 (*a*) where σ_x is axial, σ_y is peripheral and σ_z radial. Even though σ_z may be small, σ_x and σ_y may have any values, depending on the loads applied. When it comes to the shear actions, these are fixed once the principal stress values are assigned.

In order to get an idea of the character of the whole tensor which is required for complete description of the condition of stress, the device of an imaginary cut in the metal is again used.

Consider a plane section yz of the tubular specimen as shown in Fig. 12 (*b*), and a series of imaginary sections all passing through a line parallel to the x-axis. These are like a door which swings on its hinges to mark various angles on the floor yz. The force transmitted through such a section has a normal and a tangential component. The normal component has the value σ_y when the door passes through the z-axis, σ_z when through the y-axis, and intermediate values in intermediate positions.

The tangential force in the yz plane will vary in intensity as the door swings so as to make varying angles with y and z. It happens, however, that the tangential force on this door is always parallel to the yz plane. When the plane of the door passes through either of the two axes, y or z, the tangential force will equal zero. At an angle midway between them it will reach its relative maximum, τ_{yz}. The angle made by the door with y may be called φ, and the shear stress then varies with φ as is suggested in Fig. 12 (*b*); the maximum at $\varphi = 45°$ is the "principal shear stress" whose intensity is represented by τ_{yz}.

Similar relations hold for τ_{zx}, as shown in Fig. 12 (*c*), and also for τ_{xy}.

The situation will be recognized as resembling that of the biaxial case described in Part 2; it reduces to the biaxial case if one of the three principal stress components is zero. In Fig. 9, showing the tubular specimen, σ_z is zero.

By a process like that in the biaxial case, it is found that

$$\tau_{yz} = \frac{\sigma_y - \sigma_z}{2}$$

and by similar procedure

$$\tau_{zx} = \frac{\sigma_z - \sigma_x}{2}$$

and

$$\tau_{xy} = \frac{\sigma_x - \sigma_y}{2}$$

The relations between all the elements of the stress tensor at a point may be exhibited graphically by a diagram also due to Mohr, containing three circles, as shown in Fig. 13.

In the biaxially loaded tube, σ_z is negligible throughout the full range of values of σ_x and σ_y. The yz and zx circles therefore pass through the origin. The shear stress has three different relative maximum values; the largest of these is τ_{zx} when $n < 1$ and τ_{yz} when $n > 1$. Details for the orientation of τ_{zx} and τ_{xy} with respect to the cylinder are shown in Fig. 12.

The triaxial Mohr circles are sketched in Fig. 14 for various ratios of the principal stresses in tubular specimens.

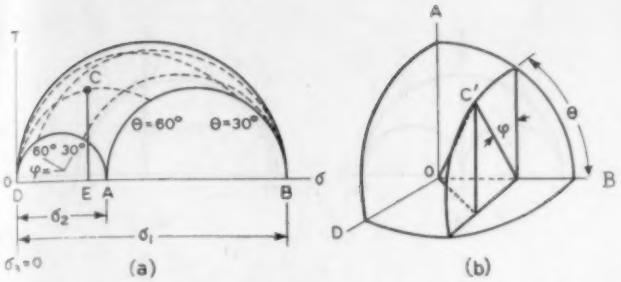


Fig. 13—Mohr's Diagram for Triaxial Stress in a Tubular Specimen

(*a*) Mohr's circles. Normal and tangential stress on oblique sections may be found by graphical constructions similar to those in Fig. 7. (*b*) The octant. The circular boundaries *BA*, *AD* and *DB* correspond to those bearing the same letters in (*a*), but the radius *OC'* is a unit vector representing *OC* in direction only.

In (*a*) the points *B*, *A* and *D* are laid off to correspond with the principal stresses, σ_1, σ_3 and σ_2, and three circles are struck on diameters *AB BD* and *DA*. The space enclosed between these circles is subdivided by a coordinate network which corresponds to the angular variables in the octant. In a way analogous to that of the biaxial case, Fig. 7, *OE* represents the normal stress on a cut at angles θ, φ, and *CE* represents the tangential stress. Each of the three boundary circles gives, at its maximum, a value of one of the three principal shear components, τ_{12}, τ_{23} and τ_{13}. For further discussion see A. Föppl Vorlesungen über Technischen Mechanik, Vol. 5, Chapters 1 and 2.

Triaxial Strain

The relationship between the components of triaxial strain as shown by the Mohr circles is exhibited in Fig. 15 in a form like that of Fig. 13 for stress.

A series of Mohr circles for different strain ratios in tubular specimens are shown in Fig. 16.

Triaxial Stress-Strain Relations

As load increases, plastic deformations progressively increase; the description of these deformations under given load forms the central object of this whole study.

It is an additional object to predict the limits of plastic energy absorption; this is equally important and is placed second only because it is more difficult.

As a progressively increasing load of a given pattern is applied to a structure, and the stresses and strains progressively increase, deflections may rise to large values. Such changes in the form of the structure will usually result in changes in the nature of the load. Thus, as a very simple example, flattening of a pneumatic tire under load increases the area of contact with the road and affects the loading in various parts of the tire.

Progressive shifts and adjustments of this kind require a very explicit definition of the circumstances before they can be accounted for. By special dispositions, as in a testing machine, a load can be held to an assigned pattern even though the form of the specimen shows great changes. Thus, by the use of self-centering devices, eccentricity of a load can be prevented in a tensile specimen even though plastic flow is not symmetrical.

The pattern of loading through a progression of increases of load level within elastic limits, or at most only a little past the yield point, may be maintained much more easily than where large and strongly nonuniform plastic deflections occur. It is therefore appropriate to imagine the former as the typical case, and it may serve as a basis for a nominal theory even when the deformations eventually become very large and the point of necking and incipient failure is approached. An understanding of this typical case is indispensable even though the case may never exactly occur; it forms a first step toward a more complete understanding of the more intricate phenomena of incipient failure, and provides a transition in the difficult adaptation of our habits of thought from terms of elastic to plastic action.

It will therefore now be assumed that the load is applied to the structure under test in a fixed pattern, so that as the load is measured all its components are held in fixed ratios to each other. Thus the tubular specimens are loaded in axial tension and by internal pressure, and in a given test these components are increased in a fixed ratio, varied only from one test to the next. This is expressed as a constant ratio n of the hoop stress σ_y to the axial stress σ_z. This stress ratio is subject to change as the form of the specimen is changed by plastic deformation, since the areas to which the loads are applied will change. For the present no account is taken of these

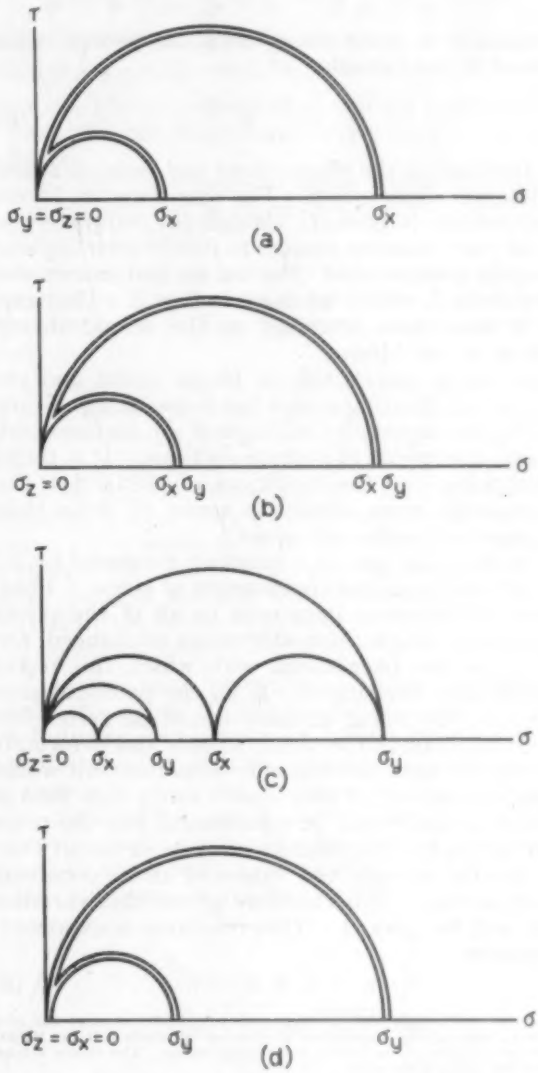


Fig. 14—Various Ratios of Principal Triaxial Stress in Tubular Specimens, Exhibited by Mohr Stress Circles

(*a*) Cylinder under pure axial tension, $n = 0$; $\tau_{yz} = 0$, $\tau_{yz} = \tau_{xy} = \sigma_x/2$. (*b*) Sphere under internal pressure, $n = 1$; $\tau_{xy} = 0$, $\tau_{yz} = \tau_{zx} = \sigma_x/2$. (*c*) Closed cylinder under internal pressure, $n = 2$; $\tau_{xy} = \tau_{zx} = \sigma_x/2$, $\tau_{yz} = \sigma_y/2$. (*d*) Open-ended cylinder under internal pressure, $n = \infty$; $\tau_{zx} = 0$, $\tau_{xy} = \tau_{yz} = \sigma_y/2$.

This is an elaboration of Fig. 8, in which components of stress in all possible orientations are considered, instead of on sections through the radial coordinate only. Two successive intensities are shown instead of three. The longitudinal, peripheral and radial principal stress components are labeled σ_z, σ_y and σ_x. As before, n is the ratio of the second of these to the first. Radial stress, σ_x, is zero throughout. The shear stress components take on the values indicated. The double lines indicate that two of the three circles shown in Fig. 13 (*a*) have coalesced due to the equality of two of the principal stresses.

latter effects, and it is assumed that the ratio of stress components retains its initial value throughout.

The Ratio of Stress-Strain Components.—The basic proposition about plastic strain caused by a given set of stress components is this: As the stress components increase in intensity each of the components of the resulting plastic strain increases in the same ratio to its corresponding stress.

The stress and strain components* to which this proposition refers are in shear, for reasons which will appear. The shear stress components are

$$\tau_1 = \frac{\sigma_2 - \sigma_3}{2}, \quad \tau_2 = \frac{\sigma_3 - \sigma_1}{2}, \quad \tau_3 = \frac{\sigma_1 - \sigma_2}{2}$$

and the strain components are

$$\gamma_1 = \epsilon_2 - \epsilon_3, \; \gamma_2 = \epsilon_3 - \epsilon_1, \; \gamma_3 = \epsilon_1 - \epsilon_2$$

The equality of shear stress-strain component ratios as expressed by the formula

$$\frac{\tau_1}{\gamma_1} = \frac{\tau_2}{\gamma_2} = \frac{\tau_3}{\gamma_3} \qquad (A)$$

is an attribute of the plastic state and rests on a basis of experimental observation. The equations are known to be approximately correct; though not completely accurate, they are accurate enough to justify their application to nominal calculations. The nature and extent of error in Equations A will be taken up in Part 5. They express what is sometimes described as the second theory or condition of von Mises.

Shear has a special role in plastic stress and strain. The fact that shearing action has a special significance is shown by the occurrence of diagonal slip surfaces and the obliquity or cupping of rupture surfaces. It is therefore not surprising that the conditions of plastic flow should be expressible more simply in terms of shear than of other aspects of stress and strain.

Shear plays its part as a quantity measured by *differences* between principal components of stress. Thus the addition of the same increment to all of the principal stresses would leave these differences unchanged, and it would leave the phenomena with which this report is concerned also unchanged. If all the principal stresses were equal, the shear stresses would be zero. Under these circumstances the shear strains and deformations would also be zero, and the only possible result would be changes in volume. Under a sufficiently high fluid pressure, steel actually will be compressed, but the pressure needed to produce significant increase in density of the metal greatly exceeds the values of stress occurring in ordinary service. It is therefore agreed that variation in density will be ignored. This condition is expressed by the equation

$$\epsilon_1 + \epsilon_2 + \epsilon_3 = 0 \qquad (B)$$

* Since the treatment no longer refers only to cylindrical tubes and now becomes more general, the convention is adopted by which σ_1 is the highest, σ_2 the intermediate and σ_3 the lowest component value. The strain values will ordinarily fall in the same order.

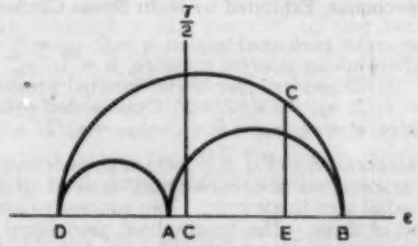


Fig. 15—Mohr's Diagram for Triaxial Strain

As Fig. 10 is to Fig. 7, so is this diagram to Fig. 13. However the zero value of σ_2 does not at all imply zero value of ϵ_2. This diagram is intended only to illustrate the fact that triaxial strain is a tensor of the same form as triaxial stress. For more details see Fig. 16.

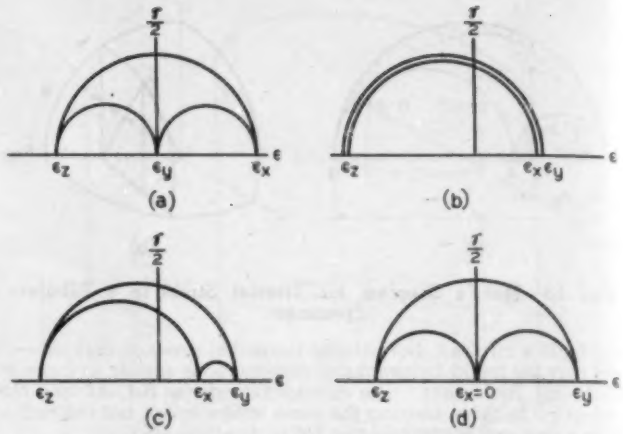


Fig. 16—Various Ratios of Principal Strain Exhibited by Mohr Circles

(*a*) Peripheral strain zero, $m = 0$; $\gamma_{zx} = 2\epsilon_x = 2\epsilon_z$, $\gamma_{xy} = \gamma_{yz} = \epsilon_z$. (*b*) Peripheral and longitudinal strains equal, $m = 1$; $\gamma_{zx} = \gamma_{yz} = \frac{3}{2}\epsilon_z$, $\gamma_{xy} = 0$. The circles $\epsilon_z\epsilon_x$ and $\epsilon_z\epsilon_y$ are identical and $\epsilon_x\epsilon_y$ has zero radius. (*c*) Peripheral strain double the longitudinal value, $m = 2$; $\gamma_{xy} = \epsilon_z$, $\gamma_{yz} = 5\epsilon_z$, $\gamma\epsilon_z = 4\epsilon_z$. (*d*) Longitudinal strain zero, $m = \infty$; $\gamma_{xy} = \gamma_{zx} = \epsilon_y = \epsilon_z$, $\gamma_{yz} = 2\epsilon_y$.

This diagram shows relations of a purely geometrical nature between the components of strain, without reference to the stresses by which they are produced. It corresponds, in the triaxial case, with Fig. 11 for the biaxial case. Care is needed to avoid confusing strain ratio m with stress ratio, $n = \sigma_y/\sigma_x$. Negative values of tensile strain denote decrease in dimensions, as in compressive deformation. But in evaluating shear strain it is better to ignore questions of sign.

This has already been mentioned, but is repeated here as expressing one of the basic experimental facts of plasticity.

Mohr Strain Circles for Assigned Stress Values.—The Mohr strain circles shown in Fig. 16 were drawn for assigned strain ratios, which, however, are not the strain ratios that correspond with the stress ratios shown in Fig. 14. In order to infer the strains to be expected from a given set of stresses it is necessary to appeal to experimental fact. In so far as these facts are now established, they are expressed in the equality of the shear stress-strain component ratios, and constancy of density, as given in equations A and B.

By the use of these ratios, a set of Mohr strain circles will now be obtained to correspond with the stress ratios exhibited in Fig. 14. In order to accomplish this, use will be made of equations A and B to establish a set of relations between shear stresses and principal strains; these will then be applied in calculation of the strain components ϵ_1, ϵ_2 and ϵ_3 which are caused by application of the assigned stress components σ_1, σ_2 and σ_3. However, it will be found that although they are necessary, these relations do not suffice for finding the actual values of strain caused by assigned values of applied stresses. To do that, use must be made of additional experimental data for the specific materials actually used, in the form of a stress-strain curve: $\tau = \text{function } (\gamma)$.

The expressions for evaluation of the shear stress-strain ratios, in terms of quantities which can be directly determined, can be obtained in general form, subject to later substitution of the specific stress-strain data. In proceeding to do this, the strain ratio $m = \epsilon_2/\epsilon_1$ will first be calculated in terms of τ_1 and τ_2. From equations A and B:

$$\frac{\tau_1}{\tau_3} = -\frac{\epsilon_1 + 2\epsilon_2}{\epsilon_2 - \epsilon_1}$$

$$\frac{\tau_2}{\tau_3} = +\frac{2\epsilon_1 + \epsilon_2}{\epsilon_2 - \epsilon_1}$$

Whence

$$m = \frac{\epsilon_2}{\epsilon_1} = -\frac{\tau_2 + 2\tau_1}{\tau_1 + 2\tau_2}$$

and in the same way

$$\frac{\epsilon_1}{\epsilon_3} = -\frac{\tau_1 + 2\tau_3}{\tau_3 + 2\tau_1}$$

and

$$\frac{\epsilon_3}{\epsilon_2} = -\frac{\tau_3 + 2\tau_2}{\tau_2 + 2\tau_3}$$

In the tube specimen, in tensile loading, when $n \leqslant 1$,

$$\sigma_1 = \sigma_x, \sigma_2 = \sigma_y \text{ and } \sigma_3 = \sigma_z$$

and when $n > 1$,

$$\sigma_1 = \sigma_y, \sigma_2 = \sigma_x \text{ and } \sigma_3 = \sigma_z$$

The case of $n \leqslant 1$ will now be followed through in detail, leaving that of $n > 1$ aside.

The quantities in equations A and B now take on the special values:

$$\tau_1 = n\frac{\sigma_1}{2}, \tau_2 = -\frac{\sigma_1}{2}, \tau_3 = (1-n)\frac{\sigma_1}{2}$$

$$m = \frac{\epsilon_2}{\epsilon_1} = \frac{1-2n}{n-2}.$$

$$\frac{\epsilon_1}{\epsilon_3} = \frac{n-2}{1+n} = -\frac{1}{1+m}$$

$$\frac{\epsilon_3}{\epsilon_2} = \frac{1+n}{1-2n} = -\frac{1+m}{m}$$

These ratios serve for the purpose of sketching the proportions of Mohr circles of strain for a variety of ratios of principal stress components; this has been done in Fig. 17.

It will be seen that the strain diagrams in Fig. 17 correspond exactly to the stress circles for the same cases* as given in Fig. 14 except as to their position with respect to the origin. The experimental facts may be summarized by saying that the Mohr circles of strain associated with a given stress are geometrically similar to the Mohr circles of stress for the same combination of components. The cases surveyed cover the full range of tensile component ratios. Intermediate cases will show intermediate stages in the progression of ϵ_2 to the right as n increases from 0 to 1.

If now a tubular specimen is subjected to a series of loads in which n is given a constant value, a series of Mohr circles for stress will be applicable as sketched in Fig. 14, where the stress is shown at two stages, the second three times the first. A similar progression of strain has not been shown in Fig. 17 for the reason that the increase in strain caused by a given increase in stress cannot be predicted solely by the relationships hitherto mentioned. The procedure consists rather in making a complete examination of the stress-strain relation for a given value of n. The most simple case is for $n = 0$, as in the standard tensile test. A procedure for utilizing such data in predicting behavior when n has other values is outlined in the next following section.

* Note that in Fig. 17 the circles are drawn for a single value of strain whereas in Fig. 14 two different values of stress intensity are shown.

4—Nominal Theory of Plastic Behavior

Two purposes are to be served by an investigation of plastic behavior of the metal in a structure:

First, the plastic deflections in a given structure under loads of specified intensity and duration can be predicted.

Second, the circumstances under which the structure can be expected to reach its limit of energy absorption can be found.

Conventional ideas, left over from a time when engineering design was concerned with simple load bearing within elastic limits, may be summarized somewhat as follows:

> It is assumed that a structure must not be loaded so as to bring the stress averaged over an extensive region to the static yield strength value. Some margin must be left between working stress and yield strength to allow for concentrations although these may be smoothed out by plastic readjustments during shakedown. It is better to hold concentrations down by generous fillets than to lower permissible working stress limits. But in any case the yield strength as found in the tensile test sets a limit which must not be exceeded if progressive fracture is to be positively prevented.

The time has come when these ideas need to be supplemented. In point of fact, many familiar structures under ordinary working conditions still have a great deal of usefulness after they have taken a permanent set; good examples are found in crane hooks and in anchor chain. Strain hardening in such structures provides a margin of strength reaching far beyond the yield strength as found in the standard tensile test. It does so, however, at the expense of residual ductility.

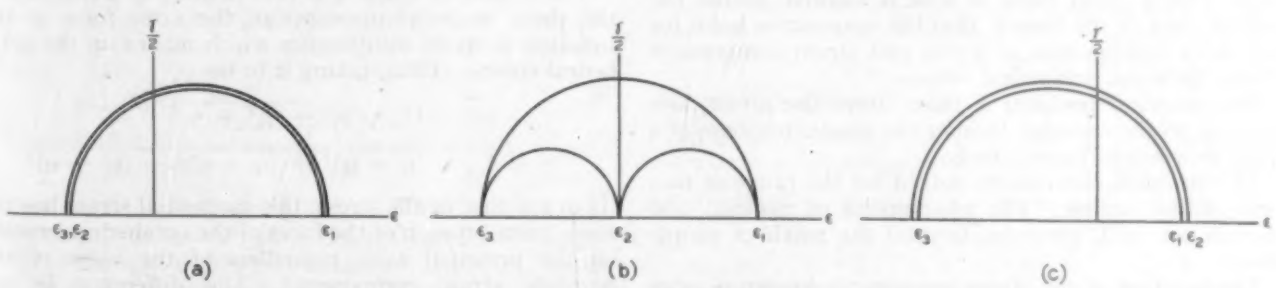


Fig. 17—Strain Corresponding to Various Ratios of Triaxial Stresses, Exhibited by Mohr Strain Circles

(*a*) Intermediate stress zero; $n = 0$, $m = -\frac{1}{2}$; $\tau_1 = 0$, $\gamma_1 = 0$; $\tau_2 = -\sigma_1/2$, $\gamma_2 = -\frac{3}{2}\epsilon_1$; $\tau_3 = \sigma_1/2$, $\gamma_3 = \frac{3}{2}\epsilon_1$. (*b*) Intermediate stress half the maximum; $n = \frac{1}{2}$, $m = 0$; $\tau_1 = -\sigma_1/4$, $\gamma_1 = \epsilon_1$; $\tau_2 = -\sigma_1/2$, $\gamma_2, = 2\epsilon_1$; $\tau_3 = -\sigma_1/4$, $\gamma_3 = \epsilon_1$. (*c*) Two stress components equal; $n = 1$, $m = 1$; $\tau_1 = \sigma_1/2$, $\gamma_1 = 3\epsilon_1$; $\tau_2 = -\sigma_1/2$, $\gamma_2 = -3\epsilon_1$; $\tau_3 = 0$, $\gamma_3 = 0$.

For the sake of generality the results are here stated in terms of the usual nomenclature, where σ_1 is the maximum tensile stress, regardless of its orientation in the body. σ_3 is the minimum tensile (or maximum compressive) stress, in tubular specimens frequently taken to be zero. σ_2 is the intermediate stress value. In these terms, the full range of significant values of n lies between zero and unity.

Simple intensity of stress is therefore not sufficient as a complete measure of strength. Failure occurs, not when stress reaches a certain limiting value, but when the reserve of ductility has been used up.

What is needed is a "theory of ductility" rather than a "theory of strength." In response to this need, the proposal made herein, for nominal use, is the theory of "octahedral" stress and strain.

The meaning and use of this theory will now be explained, but as before, it will be approached via the relatively simple case of uniaxial action.

Octahedral Stress and Strain

After the stress in a tensile specimen of medium steel passes the yield point, its elongation and the load causing that elongation are related in a way that is intricate and variable from one specimen to another. Its properties are ordinarily described in terms of three quantities:

1. Yield strength.
2. Ultimate strength.
3. Residual elongation in a specified length, or alternatively, reduction in area.

These three quantities are used in nominal strength calculations but they are not sufficient, without supplementary information or assumptions, for calculations of plastic action. For that it is necessary to know:

Octahedral stress as a function of octahedral strain

$$\tau = \tau(\gamma) \qquad (C)$$

The principles used in such calculations are now also again restated as follows:

Equality of shear stress-strain ratios

$$\frac{\tau_1}{\gamma_1} = \frac{\tau_2}{\gamma_2} = \frac{\tau_3}{\gamma_3} \qquad (A)$$

Incompressibility of the material

$$\epsilon_1 + \epsilon_2 + \epsilon_3 = 0 \qquad (B)$$

Octahedral stress as thus to be considered is a function of the stress components and octahedral strain is a similar function of the strain components. These functions will now be described.

They have the property that the value of octahedral stress τ which will accompany an octahedral strain γ is the same regardless of the particular combinations of stress components σ_1, σ_2, σ_3 and strain components γ_1, γ_2, γ_3 making up the octahedral values.

If, therefore, the curve of octahedral stress on octahedral strain can be traced from a set of observations taken with a given value of n, it is assured, within the limit of error of the theory, that the same curve holds for any other combination of stress and strain components giving the same octahedral values.

The practical problem is this: from the given data referring to the *material*, to infer the plastic response of a given *structure* to known loads.

This problem can now be solved for the range of uniform plastic action. The phenomena of necking and fracture are still, however, beyond the reach of simple theory.

The function of the stress components known as *octahedral stress* is

$$\tfrac{2}{3}\sqrt{\tau_1^2 + \tau_2^2 + \tau_3^2}$$

or

$$\tau = \tfrac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

This function has certain geometrical properties which need not be explained in detail. The name derives from the fact that if a regular octahedron, as shown in Fig. 18, is erected on the principal axes of any stress tensor, then

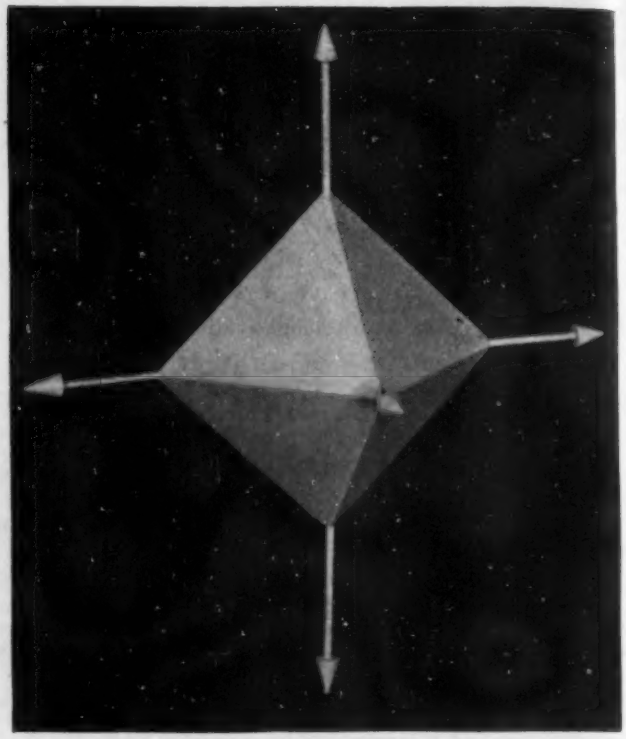


Fig. 18—A Regular Octahedron Erected on the Axes of Principal Stress
Model by A. Nadai

whatever the values of the component stresses may be, the tangential force on any one of the faces of the octahedron has the same numerical value as that on any of the other faces. Except for the coefficient, this value is the root-mean-square of the "principal shear" stresses, τ_1, τ_2 and τ_3. It is unaffected by the addition of any constant term to all of the normal stress components σ_1, σ_2 and σ_3, since the normal components enter the functions relating to shear only as differences.

The numerical coefficient which converts the root-mean-square to the octahedral value is somewhat arbitrary and is not always chosen in the same way. The usage followed here is that of Nadai, while Prager prefers a quantity

$$S = \frac{3}{\sqrt{2}} \cdot \tau$$

The *octahedral strain* γ is here defined as a function of the shear strain components of the same form as the function of stress components which makes up the octahedral stress. Thus, taking it to be

$$\tfrac{2}{3}\sqrt{\gamma_1^2 + \gamma_2^2 + \gamma_3^2}$$

$$\gamma = \tfrac{2}{3}\sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2}$$

As in the case of the stress, this tangential strain has the same value on each of the faces of the octahedron erected on the principal axes, regardless of the value of the separate strain components. The difference in the coefficient of the root-mean-square of the principal strain differences $\frac{2}{3}$ instead of $\frac{1}{3}$ as in the octahedral stress, harks back to the presence of the factor $\frac{1}{2}$ in the definition of strain on page 804 and in Figs. 9 and 10.

Different conventions for the numerical coefficient are permissible. That here adopted is in accord with a long-established practice, and the symbol adopted for octahedral strain by Nadai, γ_8, is identical with γ as here written.

In tensor analysis mathematicians have recently intro-

duced a definition of shear strain $\gamma_T = \gamma/2$ for the sake of the formal symmetry of the expression for strain

$$\gamma_T = {}^1/_3 \sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2}$$

with the corresponding one for stress.

Prager has made use of the expression

$$E = \frac{\sqrt{2}}{2}\gamma$$

Gensamer uses similar functions called "significant" stress and strain. The choice of his numerical coefficients is made so that the significant stress-strain curve is identical with that obtained from the uniaxial tensile test. Their values agree with Prager's. The symbol $\bar{\sigma}$ is used for significant stress although it is a shear stress; for strain $\bar{\delta}$ is used.

Dorn shows the same coefficients as Prager and Gensamer, but uses the terms "effective" stress, denoted by $\bar{\sigma}$, and "effective strain increment" $\alpha, \bar{\varphi}$.

Like any other average, these can take on the same values in many different ways. So far as this theory goes, different combinations of the stress components are equivalent if they have the same octahedral value and this applies also to the strains. Such a formula as this, in which stress appears only in terms of an average value, will thus be competent to deal with certain conditions governing plastic behavior, but not to determine that behavior in full detail.

The octahedral stress and strain as here defined and used together have the significant property that the integral of the stress with respect to the strain measures the work done per unit volume by the plastic deformation of the metal in the octahedron. Prager's numerical coefficient is chosen so that the factor by which the integral is to be multiplied to get this result is unity. By the usage of the tensor analysis a factor 3 is necessary. In Nadai's usage, followed in this report, this factor is 3/2.

Uniaxial Case

This is defined by the conditions that only the axial stress component exists and that the contraction ratio in each of the two directions normal to the axial load is $^1/_2$. Standard tensile test specimens approach these conditions at strains below the necking point.

In symbols,

$$\sigma_2 = \sigma_3 = 0, \epsilon_2 = \epsilon_3 = -{}^1/_2\,\epsilon_1$$

From the definitions of octahedral stress and strain,

$$\tau = \frac{\sqrt{2}}{3}\sigma_1$$

and

$$\gamma = \sqrt{2}\,\epsilon_1$$

The work of plastic deformation per unit volume of metal is

$$u = \int \sigma d\epsilon = {}^3/_2 \int \tau d\gamma$$

The factor 3/2 thus verifies in this special case the general relation between octahedral stress and strain and plastic energy as mentioned in the previous section.

The functional relation between τ and γ thus reduces in this case to the directly observed relation between σ and ϵ, except for a numerical factor. From the point of view of the uniaxial tensile test alone, nothing is gained by using τ and γ in place of σ and ϵ, especially as the orientation of the surfaces with which octahedral stress and strain τ and γ are associated is hard to visualize. But when, as in the general case, there are three σ's and three ϵ's, the reduction to a single pair, τ and γ, affords a real advantage.

Biaxial Case

The hollow cylinder presents the case of uniform distribution in which $\sigma_1 = \sigma_x$ is the axial component of stress, and $\sigma_2 = \sigma_y$, the peripheral component, for convenience expressed as $n\sigma_1$, where the case $0 < n < 1$ covers the significant range of values. It is assumed throughout that $\sigma_3 = 0$.

The practical question to be answered is this: How does the presence of a transverse component of stress σ_y affect the plastic strain ϵ_x? Since σ_2 bears a constant ratio n to σ_1 the whole case can be stated in terms of σ_x. In this sense, ϵ_x can be said to be controlled by σ_x; application of the axial load carries with it a transverse load which is not explicitly stated except in terms of n. If such a concealed transverse load exists, how will it affect the plastic response to axial load?

It is proposed to use the octahedral theory to obtain an answer, and the first move is to find the octahedral stress in terms of σ_x and n. The value is

$$\tau = {}^1/_3 \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} = \frac{\sqrt{2}}{3}\sqrt{1 - n + n^2}\,\sigma_x$$

The octahedral strain is found by introducing the special conditions of the biaxial case and it turns out, when $n \leqslant 1$, that*

$$\gamma = {}^2/_3 \sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2} = \frac{2\sqrt{2}}{2 - n}\sqrt{1 - n + n^2}\,\epsilon_x = 2\sqrt{2/3}\sqrt{1 + m + m^2}\,\epsilon_x$$

The energy absorbed in plastic flow in a tube is wholly accounted for by adding the two items of work done by the components of normal stress resulting from the two elements of load. Thus

$$u = \int \sigma_x d\epsilon_x + \int \sigma_y d\epsilon_y$$

and since $\sigma_y = n\sigma_x$ and $\epsilon_y = \dfrac{2n - 1}{2 - n}\,\epsilon_x$

$$u = \frac{2(1 - n + n^2)}{2 - n}\int \sigma_x d\epsilon_x$$

By comparison with the expressions for τ and γ in terms of σ_x and ϵ_x it will be found that the fact that energy of plastic flow per unit volume of metal is

$$u = {}^3/_2 \int \tau d\gamma$$

is again confirmed.

The values of τ in terms of σ_1 and n, and of γ in terms of ϵ_1 and n are not sufficient to give a solution for ϵ_1 in terms of σ_1 and n. What is needed for that is a functional relation between τ and γ, an octahedral stress-strain curve.

Linear Stress-Strain Curve

In order to obtain τ as a function of γ use is made of data on σ_1 as a function of ϵ_1 at a known value of n. How-

* From the equality of stress-strain ratios, Equation A and the constancy of density, Equation B 810, it is found that

$$\frac{\epsilon_2}{\epsilon_3} = -\frac{\tau_3 + 2\tau_2}{\tau_3 + 2\tau_1}, \quad \frac{\epsilon_1}{\epsilon_3} = -\frac{\tau_1 + 2\tau_2}{\tau_3 + 2\tau_1}, \quad \frac{\epsilon_2}{\epsilon_1} = -\frac{\tau_2 + 2\tau_1}{\tau_1 + 2\tau_2}$$

By substituting for τ_1, τ_2, τ_3 their values in terms of $\sigma_1, \sigma_2, \sigma_3$ these ratios may be evaluated in terms of n or alternatively of the strain ratio m with results, as follows:

$$\epsilon_1 = \frac{2 - n}{2 - n}\epsilon_1 = \frac{2 - n}{2n - 1}\epsilon_2 = \epsilon_1 = \frac{1}{m}\epsilon_2$$

$$\epsilon_2 = -\frac{1 - 2n}{2 - n}\epsilon_1 = -\frac{1 - 2n}{2n - 1}\epsilon_2 = m\epsilon_1 = \epsilon_2$$

$$\epsilon_3 = -\frac{1 + n}{2 - n}\epsilon_1 = -\frac{1 + n}{2n - 1}\epsilon_2 = -(m + 1)\epsilon_1 = -\left(1 + \frac{1}{m}\right)\epsilon_2$$

$$\gamma = \frac{2\sqrt{2}}{2 - n}\sqrt{1 - n + n^2}\,\epsilon_1 = 2\sqrt{\frac{2}{3}}\sqrt{1 + m + m^2}\,\epsilon_1$$

$$\gamma = \frac{2\sqrt{2}}{2n - 1}\sqrt{1 - n + n^2}\,\epsilon_2 = 2\sqrt{\frac{2}{3}}\frac{\sqrt{1 + m + m^2}}{m}\epsilon_2$$

ever, it is fundamental in the octahedral theory that τ is the same function of γ regardless of the combinations of stress components in τ and strain components in γ. The function τ of γ may therefore be specified by reference to the case $n = 0$; in that case, σ is found as a function of ϵ by a standard tensile test.

As a first approximation, the stress-strain curve when $n = 0$ may be fitted by an expression of the form

$$\sigma_z = a + b\epsilon_z$$

Since in the uniaxial case $\tau = (\sqrt{2/3})\sigma_1$ and $\gamma = \sqrt{2}\epsilon_1$, the relation between τ and γ becomes

$$\tau = \frac{\sqrt{2}}{3}a + \frac{1}{3}b\gamma$$

and this same relation exists between τ and γ at all values of n. By utilizing the expressions for τ in σ_x and n, and for γ in ϵ_x and n, and by solving for σ_z, it is found that

$$\sigma_z = \frac{a}{\sqrt{1 - n + n^2}} + \frac{2}{2 - n}b\epsilon_z$$

This relation is shown graphically in Fig. 19. It illustrates the risk of conclusions about ductility as drawn from simple tensile tests alone. Here is a material with yield point a, and strain-hardening quality above the yield point like that of ordinary medium steel. The stress-strain curve has been simplified, as compared with the observed curve, but this has not changed its character in any way that affects the present inferences.

The effect of the presence of the transverse stress is to stiffen the resistance of the metal to axial stress. To obtain a given axial plastic elongation a greater axial stress is needed as n increases. This effect continues without any complications up to the point at which $n = 1$ and the transverse stress becomes equal to the axial stress.

The progressive increase in resistance to deformation is also at first accompanied by a rise in apparent yield point and at $n = 1/2$ the value has gone up to $a/\sqrt{3/4}$, an increase of 15%. This change is reversed, however, as n goes on up, and at $n = 1$ the yield point has returned to its original value, a.

As n increases from this point onward, special care is needed in interpretation of the equations. As explained in the note to Fig. 7, and noted on page 809, when $n > 1$, $\sigma_1 = \sigma_y$ and $\sigma_2 = \sigma_x$. To be sure of our inferences under this convention with respect to subscripts we must revert to page 809 and follow through again from there for the new case. The result, as might be expected, is that γ has the same relation with ϵ_z or with ϵ_y as before, namely:

$$\gamma = \frac{2\sqrt{2}}{2 - n}\sqrt{1 - n + n^2}\epsilon_z = \frac{2\sqrt{2}}{2n - 1}\sqrt{1 - n + n^2}\epsilon_y$$

When combined with the expression for τ in terms of σ_z and n, and solving, it is found, when $n > 1$, as before when $n < 1$, that

$$\sigma_z = \frac{a}{\sqrt{1 - n + n^2}} + \frac{2}{2 - n}b\epsilon_z$$

The resistance to axial stress thus continues to increase as n goes on to values larger than unity, as shown by the reduced axial strain caused by a given axial stress. By sufficient increase in peripheral tension the axial elongation can be reduced to zero regardless of magnitude of the axial load, and this anomaly persists as long as the assumed conditions are maintained.

When n exceeds 2 the elongation under axial tension becomes negative, as is also shown in Fig. 19.

Parabolic Stress-Strain Curve

For the purposes of some calculations there is benefit in adopting formulas which give a closer fit than the linear formula to observed forms of stress-strain curves. Thus a good approximation to actual plastic behavior is obtained by ignoring the elastic range altogether and considering the curve to be a parabola with its vertex at the origin, so that the intercept $a = 0$. Such a curve is shown by the combination of dotted and full lines in Fig. 20. It is in point of fact observed that although some irregularities in the upper and lower yield points may occur from one specimen to another, as indicated in that figure, the rising part of the curve beyond the yield point will recur consistently in different tests of specimens of the same steel. This is as though the elastic action represented only a metastable stage, from which the passage to the parabolic plastic curve might occur at any of several levels depending on incidental circumstances.

For calculations of total energy absorption, only a negligible error is caused by following the dotted line in Fig. 20 rather than one of the full lines, especially as the action is extended and the necking point is approached.

A good fit is had by taking $\sigma_x = a + b\epsilon_x^q$. For such an approximation, the intercept a may be assumed to be zero, so that the octahedral stress is

$$\tau = \frac{2^{1/2}(1 - q)}{3}b\gamma^q$$

instead of the simple expression for the linear curve.

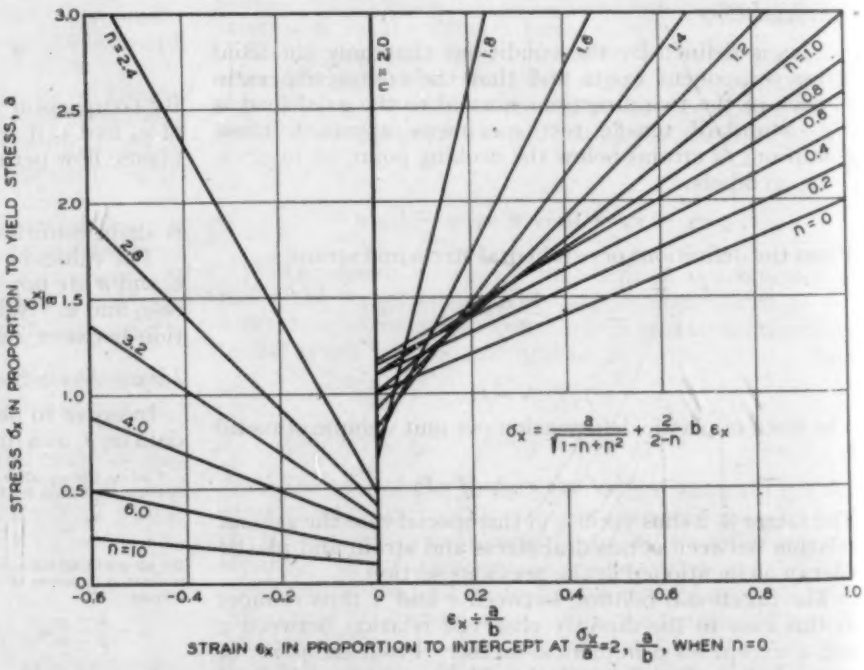


Fig. 19—Linear Stress-Strain Curves for Plastic Flow Under Combined Stress

The strain ϵ_x is produced by a stress σ_x acting in the same direction when that stress is accompanied by a transverse component of stress $\sigma_z = n\sigma_x$. When $n = 0$, these conditions reduce to those of the simple tensile test. At other values of n the presence of the transverse stress alters the response as shown. In particular, when $n = 2$, a stress σ_x produces no strain ϵ_x at all, since the contraction caused by the transverse component offsets the elongation caused by the longitudinal component of stress.

Since the equations $\tau = \frac{\sqrt{2}}{3}\sqrt{1 - n + n^2}\sigma_x$ and $\gamma = \frac{2\sqrt{2}}{2 - n}\sqrt{1 - n + n^2}\epsilon_x$ are still valid the substitution of τ and γ for the values at $n = 0$ gives

$$\sigma_x = \left(\frac{2}{2 - n}\right)^q (1 - n + n^2)^{1/2(q - 1)} b\epsilon_x{}^q$$

In some careful work by E. A. Davis[9] under the direction of A. Nadai the stress-strain curves for a specimen of medium steel were found at various values of n. They follow the parabolic form quite accurately when the value of $q = \frac{1}{4}$ is used; the corresponding value of b averaged about 112 when ϵ_x was expressed in per cent and σ_x in kips per square inch.

Inserting these values,

$$\tau = 48.4\gamma^{1/4} \text{ and } \sigma_x = \left(\frac{2}{2 - n}\right)^{1/4} (1 - n + n^2)^{-3/8} 112\epsilon_x{}^{1/4}$$

From this expression a family of curves like those in Fig. 19 has been made up, but it is considered unnecessary to reproduce them as the general nature of the result is the same.

5—Deviation of Actual Materials from the Conditions of Octahedral Theory

The equations A, B and C express conditions which must be satisfied before calculations of the sort given at the end of Part 4 are possible. In addition to these, certain other conditions have been tacitly accepted, but not given formal symbolic expression. These will now be listed and scrutinized.

Before a more complete theory of plastic behavior can be made available for application, a way must be found for introducing corrections into the calculations. It would serve a useful purpose if the extent of such needed corrections could be estimated so as to obtain an idea of the magnitude of errors arising in the different sources of error. Even this is hardly possible at present, and the only estimates of the sort which can now be made are based on comparison of the end results of calculation with the over-all results of experiment. The main lines of one such comparison will be drawn in Part 6 of this report.

An approach to the improvement of steel with respect to its plastic behavior might be made by endeavoring to obtain products approaching more closely than those now available to full compliance with the conditions to be named, or extending the range within which the agreement is good enough for practical purposes.

Homogeneity

Steel is a polycrystalline and not a homogeneous material. But shipbuilders are not crystallographers and the plasticity of the medium in which they work must be accepted as a fact without explaining it.

Homogeneity is a matter of scale; so long as geometrical details—access openings, rivet holes, plate thicknesses, tool marks—have a higher order of size than the granular structure of the metal, that structure may be ignored in describing the properties of the steel. The geometrical details of a surface of fracture, however, are often so fine that grain structure cannot be ignored when rupture is in question.

This is not a study of the conditions of rupture but rather of the conditions of flow. Rupture sets an absolute limit to flow, but generally another limit intervenes before rupture comes in question. This is the limit of stability. In a simple tensile test it is the limit at which necking begins.

The question to be answered now is therefore this: How far can the metal be strained before the straining leads to breakdown of the flow theory through inhomogeneity?

A person who sees the crystalline structure of steel as its most significant feature is tempted to say that this breakdown occurs locally at the very beginning of plastic action. This would make any theory of plastic flow invalid, and that is what many qualified persons believe to be the truth. Such a person needs to go no further with the present report, which rejects such a conclusion.

Similarly the theory of micro-cracks, if true, would seem to make a theory of flow impossible. Nevertheless, the theory of flow is able to show results in agreement with experiment. It is concluded that even the micro-cracks may be averaged out by a statistical effect.

This leaves the gross or visible defects, and these also are always present in ship steel. The commonest sort in rolled material are elongated in the direction of rolling. Their effect is to place a low limit on the transverse tension the material can be expected to withstand. Ship designers have long been accustomed to this restriction. For present purposes it can be expressed by the condition $\sigma_3 \leqslant 0$. Although this is quite different from a condition placed on the thickness component of *strain*, the fact is that in most practical cases of ship structure that also will show decrease in thickness, or at most no change, and never an upsetting effect, or increase in thickness. In other important examples of plastic action, however, upsetting effects are not uncommon.

Isotropy

Certainly no ship steel is fully isotropic, and it is equally certain that any simple theory of plastic flow must assume isotropy, expressly or tacitly. Fortunately, there are degrees of departure from strict isotropy as well as of permissible error in calculations according to the simple theory, and the matter will be discussed in terms of the acceptable limits of such errors.

To speak with understanding about isotropy one must name the property of the material which takes on different values at different orientations. Numerous tests of steel cut from rolled steel plates for the simple tension test under load parallel or across the direction of rolling have been made. Samples cut for tension parallel to the thickness coordinate are less common, since tensile loading in this direction is practically excluded in shipbuilding practice. It is usual to find values both of tensile strength and elongation that are somewhat lower across than parallel to the direction of rolling, but a deficiency of 10% would be greater than usual. Figure 19 shows that the presence of an unsuspected transverse constraint can cause a departure from expected tensile elongation far greater than 10%. For calculations such as those from which Fig. 19 was made up, a good first approximation will be had by ignoring the anisotropy.

Considering the repeated passing of the material through the rolls in the direction of the long dimension of the plate an even greater anisotropy might be expected, and its absence comes from the fact that this working is done hot. Cold working is more effective in changing plastic properties, and strong emphasis has been placed on its anisotropic effects, especially in course of tests on plastic behavior.

To be more explicit, it might be considered necessary to replace Equation C by two others, referring to longitudinal and transverse properties, as follows:

$$\sigma_l = a_l + b_l(\epsilon_l{}^{q_l}) + f_l(\epsilon_l) \qquad (C_l)$$

$$\sigma_t = a_t + b_t\epsilon_t{}^{q_t} + f_t(\epsilon_t) \qquad (C_t)$$

The introduction of a complication like this is completely unacceptable in practical calculations for ship design. For the present the only question refers to the amount of the error in taking $a_i = a_t$, $b_i = b_t$, $q_i = q_t$, and $f_i(\epsilon_i) = f_t(\epsilon_i) = 0$. The data necessary for answering this question may already exist. Some of the work done suggests even more intricate relations between stress and strain components than those in Equations C_i and C_t, but it would be useful if work already done could be expressed in these terms as an approximation.

Systematic observations of the anisotropy of medium steel should be placed in the record, and new tests made if needed. No practical purpose is served by simple demonstrations that anisotropy exists, except in promoting tests to measure its effects in materials used in ship construction.

Strain History

Ship steel as it is delivered to the yard is sometimes regarded as virgin metal, but that is for convenience only. The only way of reducing it to such a state is by some process of annealing. This brings us into the field of heat treatment and thus out of the field of practical hull design.

It must be recognized that even medium steel can be drastically altered in its properties by heat treatment and this now has increased importance in welded as compared with riveted structures. But the time has not yet come when hull steel as received is subject to specification as to heat treatment, and hull designers are not yet required to be metallurgists.

Nevertheless strain history is recognized as important in such hull parts as are subjected to stress relief. Whether or not it does so in fact, stress relief is assumed to place a structure in a virgin state, a new starting point for its strain history.

The implication of the octahedral theory is that the stress-strain curve, Equation C, correctly represents plastic stress as a single-valued function of plastic strain. Strain history then is specified only in terms of the extent of the advance toward the end of the curve at the fracture point.

This conception falls short of the whole truth in several respects. It omits all reference to intervening plastic compression, and this in fact is no great omission, since the cyclic loading of ship structure, or the reversals of stress, are all expected to remain within elastic limits. Even these have fatigue effects, but their study may be made as a project not directly involving plasticity.

Simple release of tensile load after plastic strain may be accepted as placing the metal in a new condition such that its elastic limit now lies at the maximum stress previously reached. A part of its ductility has been used up; its yield point has been crowded up toward its ultimate strength, and its reserve of plastic strain has been reduced. But the need of the structure for such a reserve may also have been diminished, if the plastic deformation was caused by a service load. Repetition of that load or any similar load smaller in value will cause no increase in plastic strain. The structure has been shaken down, like a hook subjected to proof, or a gun radially expanded.

The residual stresses incident to such adjustments of the metal to its work, are not in themselves harmful.

Some error is involved in neglect of aging effects, and these are especially marked in connection with the mode of fracture if the metal is loaded to fracture. If aging reduces the amount of strain which can be accepted after a pre-straining operation, it is important that it be known.

Closely associated with the matter of aging is that of time effects. For ordinary service conditions, the material response of the metal to stress is not greatly affected by the speed with which the stress changes its values. Of course, the mechanical effects of dynamic loading of any structure depart widely from those of static loading. But when these are correctly allowed for, even in case of ballistic loading, the residue of disparity which can be attributed to the properties of the metal is not great enough to invalidate the octahedral theory for approximate use.

Geometry

In addition to the initial effects of geometry, which are well understood in the elastic range, important consequences spring from the finite changes resulting from plastic flow. Some attempt has been made to remove this source of error by tests in which the progress of the plastic action has been interrupted and the specimen restored to its original form by a machining operation. Thus at the point of incipient necking in a tensile test the load may be removed and the specimen turned down to true cylindrical form before proceeding. This removes the immediate cause of instability, leaving only the effects of anisotropy. It is understood that this procedure permits carrying a test to higher strain values, and this indicates that the anisotropy incident to the test is less than might otherwise be supposed.

The relations between geometry and stress distribution is in some important cases quite independent of the preceding straining processes. Thus, in diaphragms under normal fluid pressure the stress can be inferred directly from the known pressure and the observed sectional profile.

The calculations involved in such a case, however, lead to the same result for all cases of the same form and proportions, with no differences attributable to absolute dimensions or scale. This has often been stated to be contrary to fact. Absolute thickness in plating, for example, is considered to be significant, so that scale models made of plating of small thickness do not give dependable predictions of the behavior of larger structures with thickness of $^3/_4$ in. or more.

The truth of such an assertion can hardly be challenged, but it is important that no unwarranted inferences be drawn. Care must be used to distinguish effects on fracture from effects on behavior in plastic flow. The use of octahedral theory in connection with fracture is outside the scope of the present treatment. Fracture sets a limit to plastic flow and is therefore pertinent to the use of steel in ship structure. But the application of octahedral theory to phenomena occurring before rupture is not thus invalidated, and that is all that is now being proposed.

Especial significance has sometimes been given to the space gradient of stress, as distinct from its intensity or its triaxiality. Whatever this may mean for a theory of fracture, its meaning for flow behavior seems to be limited to the incidental effects already noted, but with the special additional feature that the size of the region in a structure within which plastic flow occurs has a great influence on the visible consequences.

If, for example, the stress distribution is such that plastic flow within a highly localized region may lead to an adjustment of the distribution so as to eliminate high concentrations, then the result for flow behavior may be equivalent to replacing the notch causing the concentration by one of smaller acuity. Every experimenter has observed cases in which the recovery of a structure on release of load is incomplete, even though no sign of plastic flow in the structure was otherwise apparent. The reason for this is that the special extent of the affected region is too small to see.

The consequences of such action for fracture, however,

are quite distinct from those for flow, and must be considered separately.

Temperature

Cold is now recognized as the chief factor predisposing ship steel to brittle fracture. But the effects of low temperature on yield stress and on the extent of plastic flow before fracture are quite distinct from its effect on mode of fracture.

Is there any reason to believe that temperature has an effect on flow behavior not fully expressed by the stress-strain relation, Equation C? Should not a stress-strain curve obtained at a given temperature give a guide to the plastic behavior of the metal at that temperature? There seems no reason to suppose that under these conditions the octahedral theory loses its validity.

It happens that most of the work on temperature effects has been done in terms of impact loading, and it should not be overlooked that, in view of the adiabatic nature of impact tests, the initial temperature controls the temperature at which flow and fracture occur only in an indirect way which varies with other circumstances, especially geometry of the specimen. The method serves to give data on relative transition temperatures, but there is no way of converting these directly to stress-strain curves under isothermal conditions.

A correlation of transition curves by impact tests on small specimens with similar data on full-scale structures might be obtained or inferred from data on ship failures. But a set of static stress-strain curves at different temperatures would be a better generalized solution of the problem. If the energy absorption as found in such a test could be correlated with that from the impact test the latter would command increased confidence, and such a correlation is much to be desired.

Time rate of strain, or speed of loading, may affect the ultimate stress, or the yield stress, or the stress at rupture. The introduction of strain rate as a third variable thus introduces a whole new dimension into stress-strain curves. Reduction of temperature has an effect similar to that of increase in speed, as shown by McGregor.[5]

Integrated Effects and Summary

Five influences on plastic behavior have now been briefly discussed, namely, homogeneity, isotropy, strain history, geometry, and temperature. In numerous experiments on plastic behavior of ship steel these influences, though always present in greater or less degree, have been, at least in part, not controlled, either in the sense of giving them assigned values, or even of knowing what the circumstances of the tests really were.

This fact alone is enough to account for a large measure of confusion. The way to resolve this confusion is to adopt a nominal theory of plasticity as a first approximation. Deviations from any such theory are sure to be found, but a step toward understanding is already taken when they are recognized as deviations and do not have to be regarded simply as intricacies which are hopeless to resolve.

The theory here proposed is designated as the octahedral theory. It is understood to be in agreement with what is known as the "second condition of von Mises" and with the "shear strain energy criterion." The words "condition" and "criterion" have in the past been used to refer to the question: At what point in a test under increasing loads does plastic flow begin? But continuance, not inception, of plastic flow is now the most significant question in connection with plastic behavior. It happens that the quantity which determines the beginning of plastic action is also taken to play a controlling part in its continuance. This quantity is the octahedral stress as it has been used in the present report.

In order to describe the plastic response to octahedral stress the theory calls for this response to be stated in terms of octahedral strain.

The specific or elementary relation between octahedral stress and octahedral strain forms the basic fact about a given sample of metal, in whatever state of microstructure its treatment may have placed it. For the purposes of the octahedral theory the stress-strain curve, Equation C, contains all the possible or necessary data about the metal.

But this elementary "law of plasticity" must be put through some process of integration before it can lead to conclusions about extended bodies in the plastic state such as we have to deal with in the laboratory or in service. An example of such a process is given in Part 6.

6—Applications of the Theory of Octahedral Stress and Strain

The theory of octahedral stress and strain serves usefully for orientation in an unfamiliar field although it is known to fall short of complete accuracy. It performs, in a word, the functions of a *nominal* theory. Even in cases where its errors are significant, the theory serves the purpose of suggesting reasons for its inaccuracy.

New types of tests to determine the characteristics of shipbuilding material in the plastic range may be devised so as to yield better information than the ductility measurements in the standard physical tests; work along this line is underway at various laboratories and will be separately reported. Even before such information becomes available, however, some consideration of the quantitative consequences of plastic action in ship steel may give important and valuable results. A few of these will now be explored.

The Limits of Plastic Action

Two points of view may be taken with respect to the relation between flow and rupture. According to the first, metal when overstressed can respond either in ductile or brittle mode, it can either bend or break. This puts the emphasis on how to prevent rupture, and ignores the very important case in which rupture is preceded by large deformation.

But from the other point of view rupture is regarded as the terminal phase of flow, not as an alternative to flow. There is reason to believe that rupture is always preceded by plastic flow; in cases where this is not apparent it is because the flow is so uniform that no change in geometrical form can be observed, or because it is strongly localized and the extent of metal affected is so slight that it escapes notice. Thus at low temperatures the parting of a medium steel plate in tension may be so abrupt as to seem instantaneous. Even in such a case, however, it is known that the rupture is progressive in nature. At very low temperatures the extent of flow preceding rupture may be effectively zero, but with steels in use for hull construction and under conditions encountered in service this has not been found in any of numerous laboratory tests.

Such completely brittle failure is stated to have occurred in service failures. This is an anomaly that has not yet been fully explained.

In the normal course of the tensile test of a coupon of medium steel a large elongation occurs as the load is increased beyond the yield point, but without much change in the form of the specimen. Its sectional area diminishes as its length increases, but this effect is uniformly distributed over the mid-length of the specimen (if it is

not too short) which thus retains its cylindrical or prismatic form. Only after uniform strain of this sort has extended to several per cent, many-fold the elastic limit, does the plastic flow become unstable and concentrated in a local neck.

When that occurs, the octahedral theory loses its simple and direct application and requires solution of a distribution problem so difficult that no real agreement about it has yet been reached.

This limitation, which restricts the theory of octahedral stress and strain to the range of plastic action below the necking point, is more apparent than real in its effect on the determination of the plastic behavior in useful service of an extended structure. It is true that the load-elongation curve of a standard tensile coupon shows a large fraction of the whole elongation to occur beyond the necking point; however, the energy associated with this elongation is all expended within the neck, and so makes up only a small part of the total in the whole of an extended structure. The energy estimate based on octahedral theory thus has a good chance to come fairly close to the truth if necking rather than rupture is taken as the stopping point.

Failure of the structure can thus be reckoned to have begun when necking begins anywhere in the whole structure, since the energy absorbed up to that point is about all the structure can take.* This point of view seems difficult to a person accustomed to thinking only in terms of load-bearing capacity. In absence of notches the *load* carried by the structure generally cannot be increased beyond the necking point; this, however, is of secondary importance since even the increase of load beyond the yield point and up to the necking point will often also be relatively small. The benefit of a detailed consideration of plastic behavior becomes apparent only when chief emphasis is placed, not on the load, but on the energy absorbed.

The central problem to be solved in the design of a structure for resistance to damage is therefore this: How to control necking and defer rupture so as to obtain the greatest possible absorption of energy in the whole structure.

This naturally depends upon the load distribution. In a structure like the tubular test specimen, in which the distribution of stress and strain is uniform over an extended region, the whole of this region makes its full contribution to the energy absorption. Where concentrations of stress occur, the plastic flow will begin at these points. The area in which plastic flow has begun will then spread into the adjacent metal, as the load increases. In general the point at which the plastic flow begins will be the point at which necking will later appear, and this will be the only point at which the metal will achieve the full value of its contribution to the whole energy absorption.

If the load is not determinate, then it must be considered from a statistical point of view; at each point of the structure the scantlings should be adjusted to accommodate the maximum requirement at that point coming from a load of any possible distribution. This is fairly simple in designing for elastic action within given stress limits, but the problem becomes quite different in the plastic range and the solution is not clearly seen.

Even if the load distribution and the statistical problems could be completely solved, the material problem would still exist. In the effort to obtain high ductility in the finished assembly, even if the load is completely specified and the geometrical requirements completely settled, improvement can often be had by attention to metallurgical details. However, the present report deals only with the geometrical side. The octahedral theory offers a simple procedure for dealing with the phenomenon of necking in geometrical terms and points the way to the use of calculation in plastic design of a structure to be built of metal of known plastic properties.

Suppose that the elementary true stress is known as a function of true strain, as in Equation C, and can be followed out to some ultimate rupture point well beyond the necking point. This function may have such a form as that shown in Fig. 20, redrawn in Fig. 21 to illustrate another one of its properties. It exhibits an elementary relation in the sense that it is applicable only to a differential element of volume of the metal, and not to an extended volume, in the part of the curve referring to high strain values.

When this curve is available the point at which necking will occur in a simple tensile specimen may be read off by the simple device of determining the point at which the slope of the curve is numerically equal to its stress ordinate. This construction is based on a partial differentiation of load with respect to (*a*) sectional dimension and (*b*) plastic stress. Instability sets in at the point where the loss of section overtakes the strain hardening effect.

These matters have had close attention from Gensamer, whose lectures[6] deserve careful study.

Plane Diaphragm

The simplest case of plane load distribution is to be found in a circular plate of uniform thickness, stretched by expanding its rim radially from the radius a to the radius $a + \Delta a$. This is the case of a drumhead; the stress is uniform over the whole area, and the radial component σ_r is everywhere equal to the tangential component σ_t. It is called the case of "balanced biaxial tension." The thickness component σ_z is zero. The ratio $n = \frac{\sigma_t}{\sigma_r}$ is unity, so that

$$\epsilon_t = \frac{2n - 1}{2 - n}\,\epsilon_r = \epsilon_r = \frac{\gamma}{2\sqrt{2}}$$

and

$$\epsilon_z = -\frac{1 + n}{2 - n}\,\epsilon_r = -2\epsilon_r = -\frac{\gamma}{\sqrt{2}}$$

For the stress components $\sigma_r = (3/\sqrt{2})\tau$, $\sigma_t = (3/\sqrt{2})\tau$ τ and $\sigma_z = 0$. The energy per unit volume is thus $u = {}^3/_2 \int \tau d\gamma = 2 \int \sigma_t d\epsilon_r$. The fractional loss of thickness is double the fractional increase in radius.

In this simple case these relationships can be derived also from first-hand considerations, as by an artifice like that explained on page 803. The application to uniform distribution and the linear stress-strain curve of Fig. 19 is simple and straightforward and should be thoroughly understood before proceeding further.

In particular it is useful to imagine a set of relations analogous to those so completely familiar to everyone for the case of simple tension, but now applied to the case of balanced biaxial tension. For easy comparison the contrasting results are assembled in Table 1.

Bulged Diaphragm

If plane circular diaphragms could be so loaded as to produce elliptical deformation of the rim into an elliptical contour, uniform distributions of combined stress in different component ratios might be obtained. The nearest practical approach to this, however, lies in a diaphragm of elliptical contour loaded by normal pressure and deformed into a bulged surface; this produces a distribution of stress and strain which, though not

* The difference between this concept and the idea that failure occurs when the yield point is passed and plastic flow begins is very great, as may be seen by comparing the strain values involved.

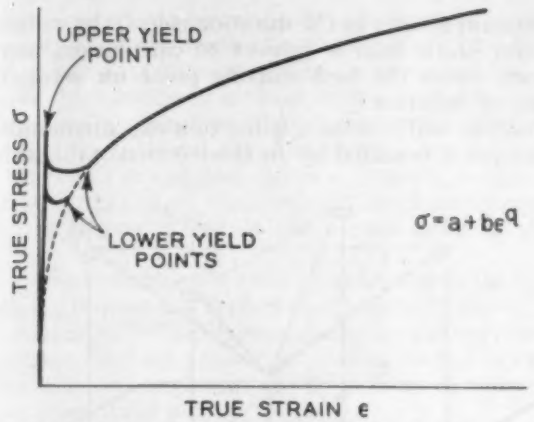


Fig. 20—Parabolic Curve Representing Plastic Stress-Strain Relationship

The upper yield point marks the limit of a metastable state which is ignored in the formulas used to represent the curve. A linear approximation to the actual curve is shown in Fig. 5; the line here drawn shows the second-order or parabolic approximation. Both refer to the curve of true stress and true strain. The dotted extension of the parabola at the lower end indicates the locus at which the parabolic curve might be picked up at various values of the lower yield point. The error involved in using the parabola at small strain values is neglected since only a small area under the curve is involved. No serious error in energy value occurs when the parabola is assumed to pass through the origin and $a = 0$.

actually uniform over the surface of the diaphragm, affords a good approximation to it in a region near the center. Variation of the rim in a series of contours of various eccentricities is used to obtain a variation in the value of n, the stress component ratio.

In the deflected diaphragm the radial and peripheral components are not distinguishable at the center point; at the rim, on the other hand, the controlling condition is that peripheral strain is zero. Even in the case of a diaphragm of circular contour, therefore, the peripheral strain will vary along a radius, and in noncircular diaphragms both the components of strain will vary, in both coordinates. This complicates matters so greatly that problems involving distribution of stress and strain over the whole diaphragm, as in estimates of total energy absorption, have not yet been solved by calculation alone. In static tests in which the deflection profile at each of the successive pressures is measured, an observed value of total energy absorbed may be found by integration of the pressure with respect to the increasing volume of the bulge.

If the diaphragm is regarded as a material specimen rather than a structure, observations can be greatly simplified by confining attention to the area near the center, where conditions are fairly uniform over a considerable region, and where failure normally begins. The method of Considère[7] may be extended by applying octahedral theory to the calculation of the limit at which plastic flow in a uniform pattern becomes unstable and is replaced by localized action analogous to necking in the tensile specimen. This is a significant example of use of the theory where more direct methods, like those mentioned in previous sections of this report, are not available. The results obtained are not in all respects satisfactory although some good agreements were obtained with data taken on tubular specimens and circular diaphragms.

Bulging of an Elliptical Diaphragm.—The cases of interest to the shipbuilder include that of the elliptical bulge as a rough approximation to a panel bounded by frames, or to a larger one supported by decks and bulkheads. It will therefore now be taken up in some detail and extended to the point of numerical application.

Table 1—Comparison of Uniaxial and Biaxial Tension

Basic Concept	Simple Tension	Balanced Biaxial Tension
Stress component ratio, n	Zero	Unity
$\sqrt{1 - n + n^2}$	Unity	Unity
Load	Total force applied to stretch the specimen	Force per unit length taken around the periphery of the drumhead, called the tension
Deformation	Total increase in length of the specimen, or elongation	Total increase in area of the drumhead
Stress	Load divided by sectional area	Tension divided by thickness
Strain	Elongation per unit length, or loss of sectional area per unit of sectional area	Increase in area per unit area, or loss of thickness per unit thickness
Octahedral stress	$\sqrt{2/3} \times$ stress	$\sqrt{2/3} \times$ stress
Octahedral strain	$2\sqrt{2} \times$ strain	$\sqrt{2} \times$ (areal) strain
Total energy absorption	Average load times elongation	Average tension times increase in area
Unit energy absorption, $3/2 \times$ integral of octahedral stress with respect to octahedral strain	Integral of stress with respect to strain	Integral of tension with respect to areal strain

The special features of plastic action in an elliptical diaphragm may first be clarified by comparison with some simpler cases of roughly similar nature.

(*a*) First consider a line passing over two sheaves at the same level and at a distance $2a$ apart, loaded at each end with a constant tension, T, and at a point

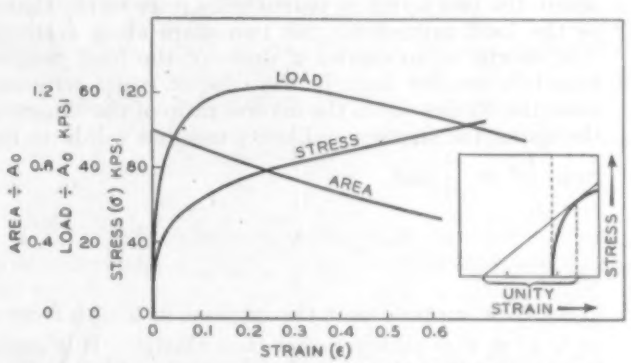


Fig. 21—Determination of the Necking Point by Graphic Construction on the Stress-Strain Curve

Note: Total load is $\sigma A = \sigma A_0 e^{\varepsilon} A / A_0$
$= \sigma A_0 e^{-\varepsilon}$
$= b A_0 \varepsilon^q \cdot e^{-\varepsilon}$

Necking begins when total load reaches its peak, since the rupture then follows immediately if external load is not relieved,

$$bA_0\left[\frac{d}{d\varepsilon}\varepsilon^q \times e^{\varepsilon}\right] = \varepsilon^q \frac{d}{d\varepsilon} e^{-\varepsilon} + e^{-\varepsilon} \frac{d}{d\varepsilon} \varepsilon^q$$

$$= -\varepsilon^q \cdot e^{-\varepsilon} + e^{-\varepsilon} \cdot q\, \varepsilon^{q-1}$$

$$= e^{-\varepsilon}\left(-\varepsilon^q + \frac{d}{d\varepsilon}\varepsilon^q\right)$$

This expression must be zero. Therefore

$$\varepsilon^q = \frac{d}{d\varepsilon}\varepsilon^q$$

Or the slope of the true stress curve must be numerically equal to the stress.

midway between the sheaves by a weight, W, less than $2T$; W sinks a distance z so that the line makes an angle ϕ with the horizon (see Fig. 22). Then

$$W = 2T \frac{z}{\sqrt{a^2 + z^2}}$$

Now suppose that support of W is shared with another line passed between sheaves at a distance $2b$ apart and disposed at right angles in azimuth with the first. Then the load carried by both lines is

$$W = W_a + W_b = 2z \left(\frac{T_a}{\sqrt{a^2 + z^2}} + \frac{T_b}{\sqrt{b^2 + z^2}} \right)$$

The deflection z will adjust itself to the values of a, b, T_a, T_b, and W in accordance with this equation.

The load is shared between the two suspensions in the ratio

$$\frac{W_a}{W_b} = \frac{T_a}{T_b} \frac{\sqrt{b^2 + z^2}}{\sqrt{a^2 + z^2}}$$

Note that if the tensions are equal, the shorter span carries the greater share of the load.

(*b*) Suppose now that the tensions and the deflection are related by the condition that the ends of the lines are fixed and their elongations elastic. The strain in the a-line is then $\sqrt{1 + \frac{z_2}{a_2}} - 1 \doteq \frac{1}{2} \frac{z^2}{a_2}$ and its tension

$$T_a \doteq E \cdot \text{sectional area} \cdot \frac{1}{2} \frac{z^2}{a^2}$$

and similarly in the b-line. Load and deflection are related by the equation

$$W = W_a + W_b = E \cdot \text{sectional area} \cdot z^3 \left(\frac{1}{a^2 \sqrt{a^2 + z^2}} + \frac{1}{b^2 \sqrt{b^2 + z^2}} \right)$$

where the two terms in parentheses refer to the shares of the load carried by the two suspending systems. The shorter span carries a share of the load proportionately greater than in the case of equal tensions; since the strains are in the inverse ratio of the square of the spans, the stresses and hence tensions will be in the ratio $\frac{T_a}{T_b} = \frac{b^2}{a^2}$ and

$$\frac{W_a}{W_b} = \frac{b^2 \sqrt{b^2 + z^2}}{a^2 \sqrt{a^2 + z^2}}$$

(*c*) Now suppose that the increase in length from a to $\sqrt{a^2 + z^2}$ is plastic rather than elastic. If it could be assumed that the strain hardening would just offset the reduction in area, the tensions in both suspensions would remain constant and equal to each other at the value of yield stress times area. Load would be shared as in Case (*a*).

Even under the simplified conditions of Case (*c*) the load-sharing ratio moves toward unity, as the deflection z increases. With other more intricate relations between plastic stress and strain more intricate progressive changes in this ratio will occur.

Under certain conditions, when hardening fails to keep pace with loss of section, a point is reached at which the total load passes a maximum and further increase of deflection is accompanied by a falling off of load. Or, if load is maintained, as when it is applied as a dead weight then this limiting point marks the beginning of catastrophic failure. It is the absolute limit which the structure can carry under static conditions. Though a transient load, if brief enough in duration, may exceed this limit by an amount greater as the duration is less, the value of the limiting static load is subject to calculation, and once known, forms the best starting point for estimates on transient behavior.

Analysis will now be applied to a cap surrounding the center point, bounded by the intersection of the surface of

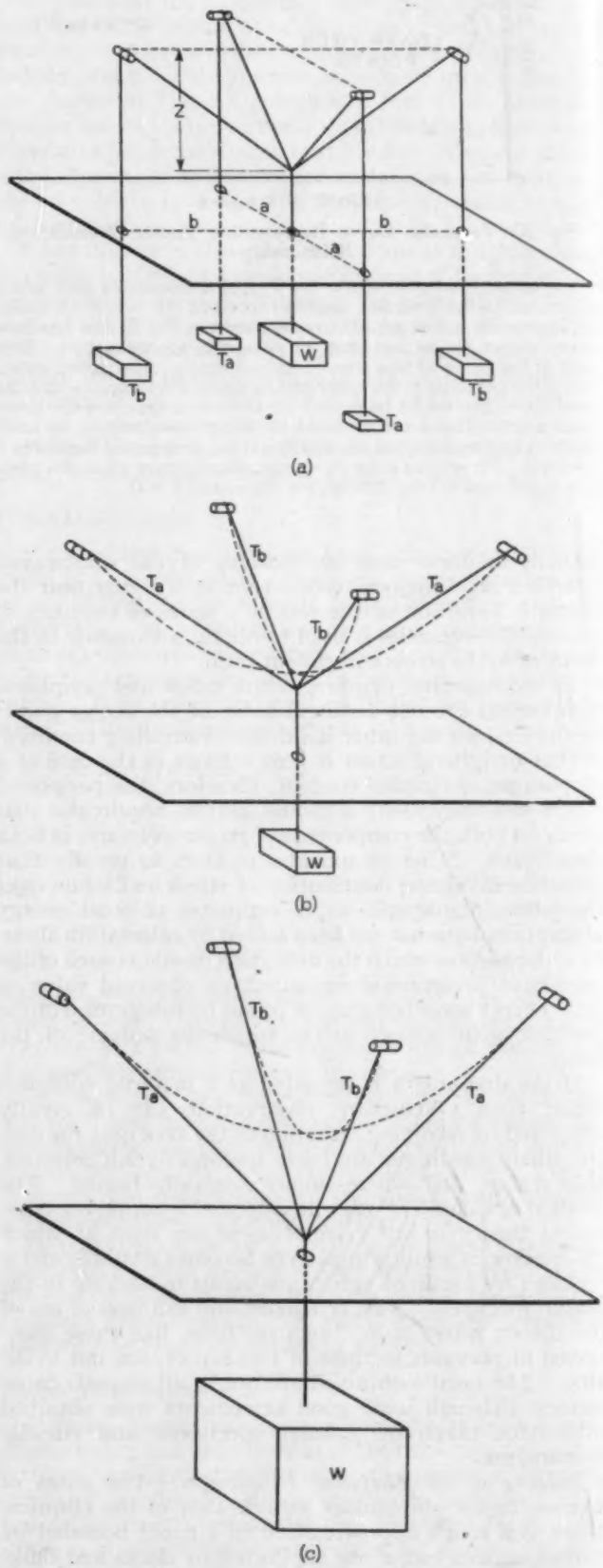


Fig. 22—Adjustment of Deflection Lines Sharing Support of an Applied Load

the diaphragm with a circular cylinder of radius c, whose axis is normal to the surface at the center. This boundary thus has a circular projection on the x-y plane, but the curve does not lie in a plane, being nearer the plane of the rim at the ends of one diameter than the other.

The section is taken after the bulging has reached a given stage. The contour radius c is small, so that the departure of the bulged surface from the plane tangent at the center is everywhere of the second order of small quantities.

This initial condition is then compared with that after the bulging process has been carried a little further. The new condition is defined geometrically for the purposes of the problem and an answer is sought for the question whether the new position corresponds to an increased value of pressure or not.

The geometrical form into which the initial surface is transformed is in fact determined by the conditions of the problem and is strictly not subject to arbitrary choice. However a choice is necessary for practical reasons of calculation; this choice will not be wholly arbitrary but plausible, and is one which is known to be approximately correct. This procedure reduces the problem to one which may be stated thus: "If the properties of the material are such that the progressive forms through which the surface passes are as described, then what loads will occur at the various stages of the action?" The question we would rather solve is this: "Given a material of stated properties, what form will the bulge have at various stages of the action?" This latter problem has not yet been solved, but it will be seen that attention to the former one will yield pertinent returns.

For a first approach to the matter the cap will be treated as a curved membrane in which the tensions are the significant elements of the force action. When the components of tension are equal, the problem is greatly simplified; the difficulties that arise when unequal components of tension are admitted are those we must find a way to cope with. But some of them we will explicitly ignore. Thus attention will be given mainly to the tensions and only incidentally to the shear stresses. This does not mean that shear stresses are assumed to be zero; on the contrary the octahedral theory is based on expressions involving shear rather than tension explicitly. But the theory permits estimate of the tensions; these are the most important actions and the only ones external to the cap that will be considered.

The cap is like the fabric of an awning, stretched by stops led to a jackstay. Each stop is assumed to lie in a plane normal to the edge contour of the surface and also in the plane tangent to the surface at the point where the stop takes hold.

The surface departs from the plane tangent at the center point by distances of the second order, but it is these which figure in the relations between the geometry and the force actions. Fortunately these relations can be stated in terms of quantities not at all infinitesimal, namely, the radii of curvature, whose values are as follows:

$$r_x = \frac{a^2}{2z_0^2} \qquad r_y = \frac{b^2}{2z_0^2}$$

The most important geometrical feature of the surface is the fact that its meridional sections have curvatures which vary in azimuth. Let the x-axis be laid in the direction of the minor axis of the contour ellipse. The x-radius of curvature, r_x, will be the minimum value, and the maximum radius will be r_y. As the angle θ increases from 0 at the x-axis to $\pi/2$ at the y-axis, the radius takes values given by

$$\frac{1}{r_\theta} = \frac{\cos^2\theta}{r_x} + \frac{\sin^2\theta}{r_y}$$

Conditions in this quadrant are repeated in the other three.

The angle ϕ made by the tensile stop with the reference plane is $\phi_\theta = c/r_\theta$ where c is the radius of the cap.

In the awning, radial tensions are set up by manipulation of the stops. In the diaphragm they are determined by the plastic properties of the material. The procedure by which the determination of the plastic stresses in the bulge is to be followed is through the plastic strains and the stress-strain relation. When the stresses are known the load can be found, and the load maximum gives the static limit which is the quantity of primary significance for the structure.

To find the energy-absorbing capacity of the structure, which measures its value under transient load, its load-deflection curve must be obtained.

Geometry of the Parabolic Profile.—In proceeding to calculate the load-deflection curve of a bulged diaphragm we will draw upon three resources:

(*a*) The octahedral theory.
(*b*) The observed stress-strain curve for the given material.
(*c*) The geometrical properties of the paraboloidal form, assumed to be exact, known to agree well with profiles observed in diaphragms of circular contour (see Figs. 23 and 24).

The profile of the diaphragm cut by the y-z plane will now be analyzed with respect to some of its geometrical properties. It may be regarded as the section of a surface of revolution if that seems to simplify matters, leaving the complications that follow from using a different contour radius a, along the x-axis, to be taken up later.

The equation of this profile is

$$z = z_0(1 - (y/b)^2)$$

and its slope

$$\frac{\partial z}{\partial y} = -2\frac{z_0}{b}\cdot\frac{y}{b} = -k$$

This fraction recurs frequently and will be designated $-k$, a dimensionless number.

The radius of curvature is given by

$$\frac{r_y}{b} = \frac{(1 + k^2)^{3/2}}{2\dfrac{z_0}{b}}$$

The bulged diaphragm will now be expanded so that z_0 moves out to $z_0' = z_0 + \Delta z_0$ and the new profile has the equation

$$z' = z_0'(1 + (y/b)^2)$$

This is not accomplished by moving each point y,z to a new point y,z'. There is a radial component, v, of deformation such that a point originally at y, zero moves first to $y + v$, z, and thence to $y + v'$, z'.

Observation justifies the further assumption that v has a series of values such as will make the path of a given particle of metal orthogonal to the profile, so as always to follow the normal direction.

The distance by which the particle moves in the axial direction is nearly

$$\Delta z = \Delta z_0(1 - (y/b)^2)$$

since v is small. Since the slope of the normal is the negative reciprocal of the slope of the tangent,

$$\Delta v = k\,\Delta z = \frac{2y}{b^2}(1 - (y/b)^2)z_0\,\Delta z_0$$

whence

$$v = \frac{y}{b^2}(1 - (y/b)^2)z_0^2$$

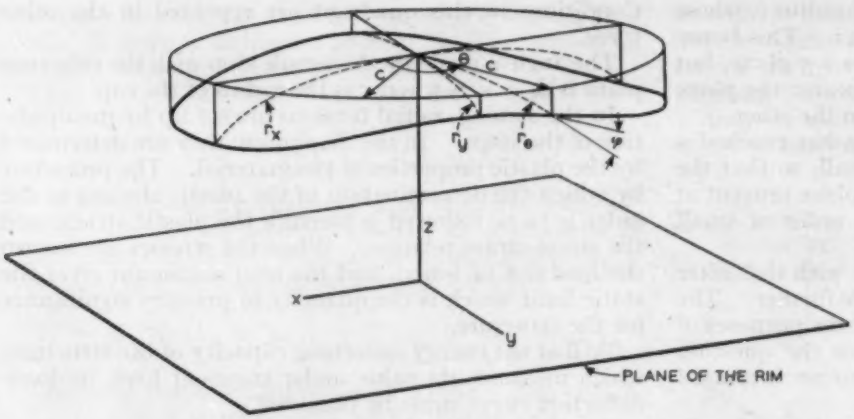


Fig. 23—Geometry of the Circular Cap

These conditions are sufficient to define the value of the radial component of strain, a purely geometrical quantity. Its value* is

$$\epsilon_y = \text{limit}_{\Delta y \to 0} \frac{\sqrt{(\Delta y + \Delta v)^2 + \Delta z^2} - \Delta y}{\Delta y}$$

$$= \sqrt{\left(1 + \frac{dv}{dy}\right)^2 + \left(\frac{dz}{dy}\right)^2} - 1$$

But

$$\frac{dv}{dy} = (z_0/b)^2(1 - 3(y/b)^2)$$

and

$$\frac{dz}{dy} = -2\frac{z_0}{b} \cdot \frac{y}{b}$$

This gives

$$\epsilon_y = \sqrt{\left(1 + \left(\frac{z_0}{b}\right)^2\left(1 - 3\left(\frac{y}{b}\right)^2\right)\right)^2 + 4\left(\frac{z_0}{b}\right)^2\left(\frac{y}{b}\right)^2} - 1$$

and by the same reasoning

$$\epsilon_x = \sqrt{\left(1 + \left(\frac{z_0}{a}\right)^2\left(1 - 3\left(\frac{x}{a}\right)^2\right)\right)^2 + 4\left(\frac{z_0}{a}\right)^2\left(\frac{x}{a}\right)^2} - 1$$

For further analysis only the metal at the center of the diaphragm ($y = 0, x = 0$) will be considered. It is convenient also to express the values in terms of the radii of curvature, so that from this point onward,

$$\epsilon_y = \left(\frac{z_0}{b}\right)^2 = \frac{z_0}{2r_y}$$

and

$$\epsilon_x = \left(\frac{z_0}{a}\right)^2 = \frac{z_0}{2r_x}$$

Strain and Stress at the Center.—z_0 is the deflection from the plane of the contour and is not related to the cap; so that

$$\frac{\epsilon_y}{\epsilon_x} = \frac{a^2}{b^2} = \frac{r_x}{r_y} = m$$

The limits of variation of m are unity and zero.

Now by the relations on page 811 the ratio between stress components, n, may be inferred from the ratio between the strain components m. We have

$$m = \frac{\epsilon_y}{\epsilon_x} = \frac{2n - 1}{2 - n}$$

whence

$$n = \frac{\sigma_y}{\sigma_x} = \frac{1 + 2m}{2 + m}$$

The values of n obtainable range from unity for a diaphragm of circular contour to one half for one greatly elongated.

Turning now to consideration of stress it is necessary to make careful distinction between different values, for all of which the symbol σ is used. At every point in a discussion like that which follows, the reader must have a clear answer to the questions: What particular stress value is here intended? Is it a limiting value? Or is it the value produced in a given structure by a given load? Is the structure a test specimen or a service assembly? Is the load causing the stress known or does the word "stress" refer only to the permitted value which may be used in design for given service, as based on experience in that service?

The stresses now to be considered are those at the center of a diaphragm bulged to a central deflection z_0 by fluid pressure, P. One of the principal stresses is taken to be zero, and the ratio of the smaller to the larger of the other two is n.

Upon original formation of the bulge by plastic action, an octahedral strain

$$\gamma = 2\sqrt{2/3}\sqrt{1 + m + m^2}\,\epsilon_x$$

is attained, and the octahedral stress corresponding to this can be found from the stress-strain curve. On release of the pressure the diaphragm behaves in an elastic manner.

If, beginning at zero, the pressure on a diaphragm thus previously bulged is gradually increased, the stress values increase proportionately to the pressure and in the given ratio, in accordance with the formulas, up to a limit equal to the pressure previously applied to produce the bulge.

Beyond this point something quite different happens. z_0 increases to z_0', a^2 and b^2 remain unchanged, but the radii of curvature diminish from

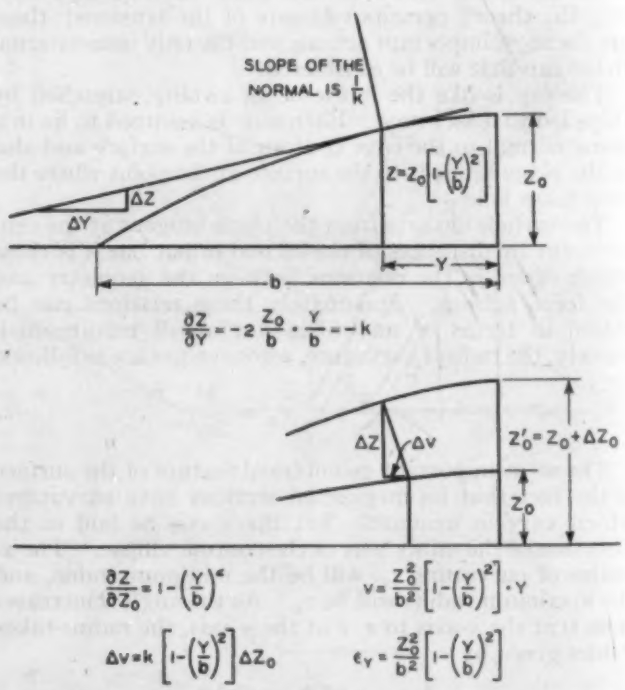


Fig. 24—Geometry of the Parabolic Sections of a Bulged Diaphragm

* The elegant form of the exact expressions which follow was given them by Dr. W. R. Osgood. See also reference 9.

$$r_x = \frac{a^2}{2z_0} \text{ to } r_x' = \frac{a^2}{2z_0'}$$

and from

$$r_y = \frac{b^2}{2z_0} \text{ to } r_y' = \frac{b^2}{2z_0'}$$

The plastic strains in the metal are thus increased from

$$\epsilon_x = \frac{z_0}{2r_x} \text{ to } \epsilon_x' = \frac{z_0'}{2r_x'}$$

and from

$$\epsilon_y = \frac{z_0}{2r_y} \text{ to } \epsilon_y' = \frac{z_0'}{2r_y'}$$

The thickness diminishes from h to h^1 where

$$\ln \frac{h}{h_0} + \epsilon_x + \epsilon_y = \ln \frac{h'}{h_0} + \epsilon_x' + \epsilon_y' = 0$$

and the octahedral strain increases to

$$\gamma' = 2\sqrt{\frac{2}{3}}\sqrt{1 + m + m^2}\,\epsilon_x'$$

The basic question is this: What new pressure value, P', is needed to cause the geometrical changes involved in increase of z_0 which have been described?

In order to answer this question stress must be viewed in a different way, as the limiting value at which unaccelerated plastic flow can be maintained. This is the stress of the materials engineer, and in the familiar curve which characterizes a given material it is shown as a function of strain. A good short expression for it sometimes used is "plastic stress."

To find the limiting value of pressure which will cause increase in the bulge, the previous strain history of the metal must be known. It will be assumed to have consisted of strain hardening, by which the limit of elastic action has been raised to the point on the stress-strain curve corresponding to the previous strain.

Ordinarily the stress-strain curve is visualized in terms of the simple tensile test. The basic thesis of the octahedral theory is that strain hardening may be described solely in terms of the octahedral values of stress and strain and that the results are identical, regardless of what components, both of stress and of strain, may enter into the octahedral values.

If the pressure applied causes a stress less than the plastic limit the deflections remain within elastic ranges; to cause plastic flow the stress must be raised to the limit designated as the plastic stress. The pressure required to accomplish this can now be calculated.

The Plastic Deformations.—The specific steps by which the octahedral theory is used in calculating the plastic behavior of an elliptical diaphragm are as follows:

(*a*) In terms of a/b, the eccentricity of the elliptical contour,

$$\frac{\epsilon_y}{\epsilon_x} = m = \frac{a^2}{b^2} = \frac{r_x}{r_y} = \frac{2n - 1}{2 - n}$$

and

$$\frac{\sigma_y}{\sigma_x} = n = \frac{1 + 2m}{2 + m}$$

(*b*) Choose a series of deflection values, expressed as z_0/a. This fixes r/a, though the approximate value $a/2z_0$ is only a rough approximation valid when z_0/a is small. The exact value* is

$$\frac{r}{a} = \frac{1}{2}\left(\frac{a}{z_0} + \frac{z_0}{a}\right)$$

(*c*) From the value of r/a exact values of the strains are found by

$$\epsilon_x = \frac{z_0/a}{2r_x/a}$$

and

$$\epsilon_y = \frac{z_0/b}{2r_y/b}$$

Then

$$\epsilon_z = -(\epsilon_x + \epsilon_y)$$

(*d*) The original thickness h_0 is thus reduced to the value

$$h = h_0 \ln^{-1} \epsilon_z = \frac{h_0}{e^{(\epsilon_x + \epsilon_y)}}$$

The sign need cause no confusion since h is always less than h_0.

(*e*) From the principal strains the octahedral value is found by the convenient expression:

$$\gamma = 2\sqrt{\frac{2}{3}}\sqrt{1 + m + m^2}\,\epsilon_x$$

The corresponding value of τ is taken from the stress-strain curve, and the principal stresses are

$$\sigma_x = \frac{3}{\sqrt{2}\sqrt{1 - n + n^2}}\,\tau$$

$$\sigma_y = n\sigma_x$$

$$\sigma_z = 0$$

This completes the calculation of the various quantities relating to the plastic deformation of the diaphragm as made by the octahedral theory. It may be extended to any value of a/b, giving values of n between one-half and unity.

The results of a set of such calculations are shown in Fig. 25. They are given in terms of load and deflection, although the conversion of stress into load values will be mentioned separately.

Deviation of the results thus predicted from those found in direct observation may indicate that the conditions necessary for application of the octahedral theory are not satisfied by the material used. The evaluation of these discrepancies is an important objective of current research.

Relations Between Stress and Load.—The basic relation between the hydrostatic pressure load and the stress components in any curved membrane is

$$\frac{P}{h} = \frac{\sigma_x}{r_x} + \frac{\sigma_y}{r_y}$$

In the case of elastic action h, r_x and r_y figure as constants. But for our present purpose all three are variable. By making use of the geometrical relations which have been developed we have

$$P = h\frac{\sigma_x}{r_x}(1 + nm)$$

This is found to pass through a maximum value when the stress-strain curve is represented by an expression of the form

$$\tau = \text{constant} \times \gamma^{1/4}$$

This maximum marks the point at which deflection might increase without rise in pressure value, provided the load is backed by enough energy. It gives the prediction of the octahedral theory as to the limit to which a structure of the given type may be pushed in service.

These limits are exhibited in Fig. 25 for the different cases studied.

* This very convenient and exact relation comes from Lt. Comdr. L. W. Sprinkle.

7—Summary and Conclusions

The elements of a nominal theory by which plastic stress and strain may be approximately calculated have been presented, first, by explanation of the quantities involved and their relations with each other; next by application to tubular specimens, a case of uniform distribution of stress ratio and of stress intensity. Comment bearing on the nature of the errors to which this theory is subject has also been made, and this serves to indicate the nature of experimental work now going on with the purpose of reducing these errors. The more elaborate theory which would be needed for calculations which would take account of the various effects mentioned has not been considered.

In so far as the peculiarities of different metals or of different parts of the same piece of metal can be stated in terms of the stress-strain curve, as indicated by Equation C, local application of the theory is possible. This leads, however, into difficulties of the sort occurring generally in *distribution* problems. These difficulties are great enough even when the material involved is homogeneous and isotropic. The errors caused by departure from these conditions are therefore ignored in what follows.

A great source of difference between the simpler condition of elasticity and that now considered lies in the nonlinearity of the equation of condition, the stress-strain relation. The resource drawn upon consists in devising a geometrical condition which can be shown to be satisfied in a practical case with a sufficient accuracy. The classical example of such a procedure is found in ordinary flexure theory; the need for it in that case arises not through nonlinearity in Hooke's Law, but in the cross

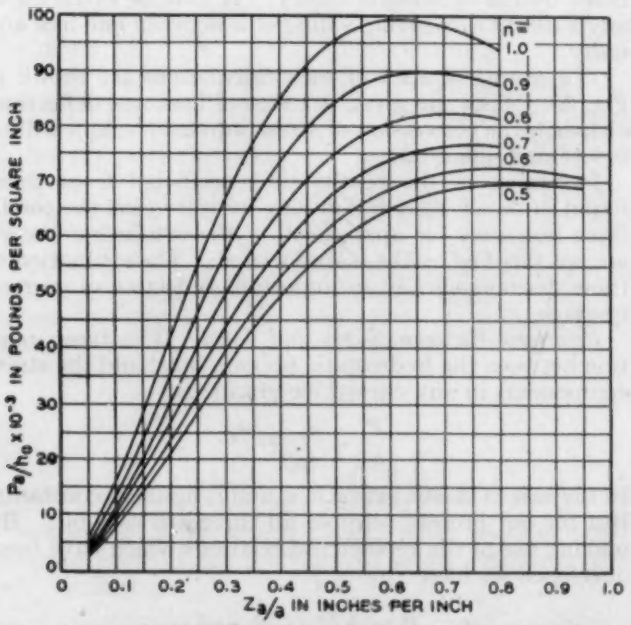


Fig. 25 (*a*)—Pressure Required to Produce a Given Central Deflection in an Elliptical Diaphragm Calculated by Octahedral Theory

The eccentricity of the ellipse is related to the stress ratio n by the equation $\frac{a^2}{b^2} = \frac{2n-1}{2-n}$. The pressure P required to produce central deflection z_0 in a diaphragm of minor semi-diameter a and thickness h_0 is given by the curves. The corresponding intensity of stress at the central point is given by:

$$\sigma_x = \frac{\frac{P \cdot a}{h_0}}{\frac{z_0}{a}} \cdot \frac{\sqrt{1-n+n^2}}{2-n}$$

$$\sigma_y = n\sigma_x$$

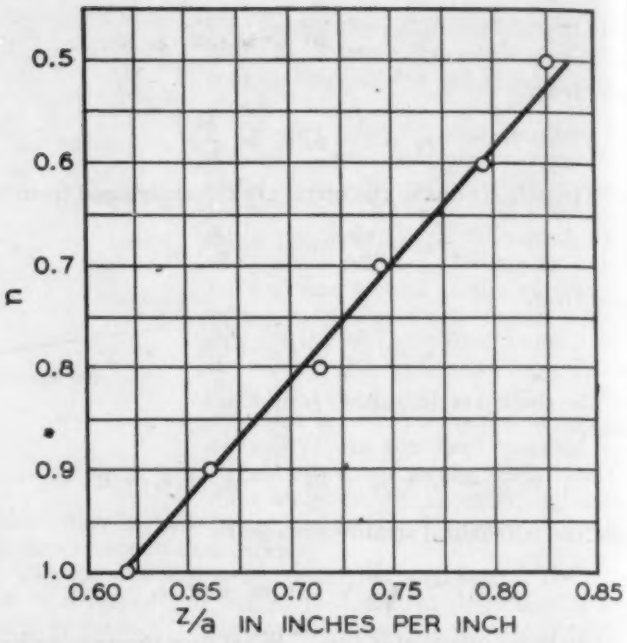


Fig. 25 (*b*)—Displacement of Maximum Pressure Point with Changing n

relations between stress and strain components associated with Poisson's Ratio. In the present case the nonlinear stress-strain curve presents an additional difficulty. The method used consists essentially in finding an adequate description of the observed strains in geometrical terms by a process like that of curve fitting, application of an analytic expression to the approximate statement of empirical facts. From these data stresses are inferred, and integrated to give loads. Confirmation of these by observation is the validation of the process. It cannot be strictly justified logically but it affords a condensed description of the phenomena.

This method of analysis has then been undertaken in one example, that of an elliptical diaphragm. It gives an important result well confirmed by observation, namely, that the load on a diaphragm rises to a maximum value beyond which lies instability and finally fracture. The deformation limit at which this occurs in a circular diaphragm is at least roughly as observed; the predicted variation with eccentricity and so with stress ratio, giving higher deformation limits at lower values of the second stress component, has not been confirmed.

A similar analysis of tensile bars of flat section is in hand but has not been completed and will be reported separately. Higher strains occur in diaphragms than in tensile bars before instability sets in, but this fact alone is not conclusive. It cannot be inferred from the lower ductility in tensile bars, where the transverse components are small, that ductility in diaphragms must rise as transverse components increase in intensity; tensile bars and diaphragms are different cases in which the whole geometrical patterns of strain and of load are different, and easy inferences drawn from one case for application to the other may be misleading. Even though it be accepted that all the data needed about plastic behavior of a metal are contained in its stress-strain curve, we are still quite unfamiliar with the consequences of changes in form of the stress-strain curve, as they may appear in extended structures.

It is thus that the *distribution* problem takes priority over other aspects of phenomena of plasticity as these are viewed by the ship designer. His main resource is in the choice of form and dimensions for the parts which are to be joined to make a ship. Our whole purpose has been

to find a way to make this choice so that the ship may perform acceptably when loaded into the plastic range.

The results here set forth may seem far removed from the point of direct application to the design of ship hull structure, and it is quite true that much work remains to be done before standardized calculations of this sort applicable in routine design can be laid out for adoption. Nevertheless some basis for predicting plastic behavior of structures is necessary. Perhaps this paper indicates that prediction of plastic behavior of ships in service may sometime pass from the realm of rule-of-thumb and intuition into the more exact practice of calculation.

It is hoped that the ideas thus presented may be developed further to the point of use in design practice.

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Original Resistance Welder Design for Production of U. S. Navy 40-MM Ammunition Boxes

By F. M. Pence*

IN April 1943, we of Thermador were manufacturing 40-MM ammunition boxes for the U. S. Navy. We had started early in 1942 to make this box and had attained a production rate of about 2000 boxes per shift. One shift had actually produced 2400 assemblies.

All types of resistance welding were used on the line: flash, roller, tack, seam, gun and projection welding.

Navy inspection of these boxes was very thorough and during the first year of manufacture we had all learned a great deal about jigs and welding technique. Also, a shortage of man power and the resultant necessity of using female operators had compelled us to develop and build a number of single-purpose jigging and welding machines. With these the operators had only to load the parts into a machine and hit a button to perform the operation. In some cases these machines were even made to eject the box or parts from the machine, so consequently, very little physical effort was required of the operator.

In 1941 we had in our plant four spot-welding machines. In 1944, on the ammunition box line alone, we had a connected load of 2520 kva.

Because the nationally known welder manufacturers were buried in orders for machines, we were forced to make these single-purpose welders in our own shop. A total of eight such machines were made by us for this assembly line, and all were made to perform smoothly and efficiently. Ninety-six man-hours per shift were saved by these home-made Thermador welders.

Naturally we made some mistakes, but as our experience grew we learned that if the principle of operation is sound, an automatic welder can be made for any high-production setup where fatigue and handling are problems.

Perhaps the most spectacular and interesting welder we made was one which wrapped a heavy band around the box bottom and welded it in place accurately. The box bottom was of 19-gage steel and was drawn in the shape of a shallow pan. It was about 11 in. square with $2^1/_4$ in. radii in the corners and was about $1^1/_2$ in. deep. The band was 10-gage steel, $^3/_4$ in. wide, and the length just enough to encircle the bottom and have the two ends butt together.

In the beginning we had made this band by cutting it to length and forming it in two die operations to the contour of the box bottom. Then we would clamp the band around the box bottom in a jig and tack weld the band to the bottom, after which we would take the two pieces out of the jig and pass them to another operator who would add the required number of welds. Six welds on four sides were required, and the butt ends had to be welded tightly to the box bottom. Also, the band had to be welded uniformly so that the edge of the band was 0.250 ± 0.020 in. from the bottom of the pan.

This band served a double purpose; it not only reinforced the box bottom, but it served as a stop when the boxes were stacked and nested vertically.

Four operators were required to perform this welding operation at 200 per hour, in addition to the labor required to form the band into shape.

The above jigging and welding operation was a rather difficult one, as the bands and bottoms had to be pounded and cramped into the jigs and then pounded out of the jigs when the welding was completed. Girls didn't like the job and had to be relieved quite often. Then, too, the price we were getting from the Navy for these boxes was always reduced with each new order we obtained, so in looking over the processing of the box, we hit upon the idea of welding this band to the box bottom using a rotating die, and then later we decided to try the ultimate. That is, starting with a straight band, we would form the band around the bottom and weld it progressively, at the same time.

Thermador is a relatively small plant. Normally we employ about 500 people in the factory. We have no elaborate tool-designing department, and usually the design is a working drawing showing the salient features and requirements of the machine to be built. We have some clever young mechanics here and after talking over this idea with one of them and selling each other on the feasibility of it, we started the job of making the machine.

Figure 1 shows our layout drawing, and shows merely the most essential details. The machine was completed in just about five weeks, and was largely the result of day-to-day consultation and decision.

When completed and tried out for the first time, we found that the welding roller covered too great an area of the 10-gage band to make a good weld. Then we thought of embossing projections on the band to diminish the weld area. This we did, and the problem was solved.

The die that was used to cut the band to length was reworked to also emboss these projections into the band at the places we wished the welds to be made.

We used a 100-kva. welding transformer with an 8-tap control, which we purchased from the Acme Electric Welder Co. of Los Angeles. We were not sure that we would need so much power, but we wished to have enough.

For the motive power for rotating the die, we bought a 2-hp. back-geared motor with variable speed control and equipped with a powerful solenoid brake. This motor

* Vice-President, Charge of Engineering, Thermador Electrical Mfg. Co., Los Angeles, Calif.

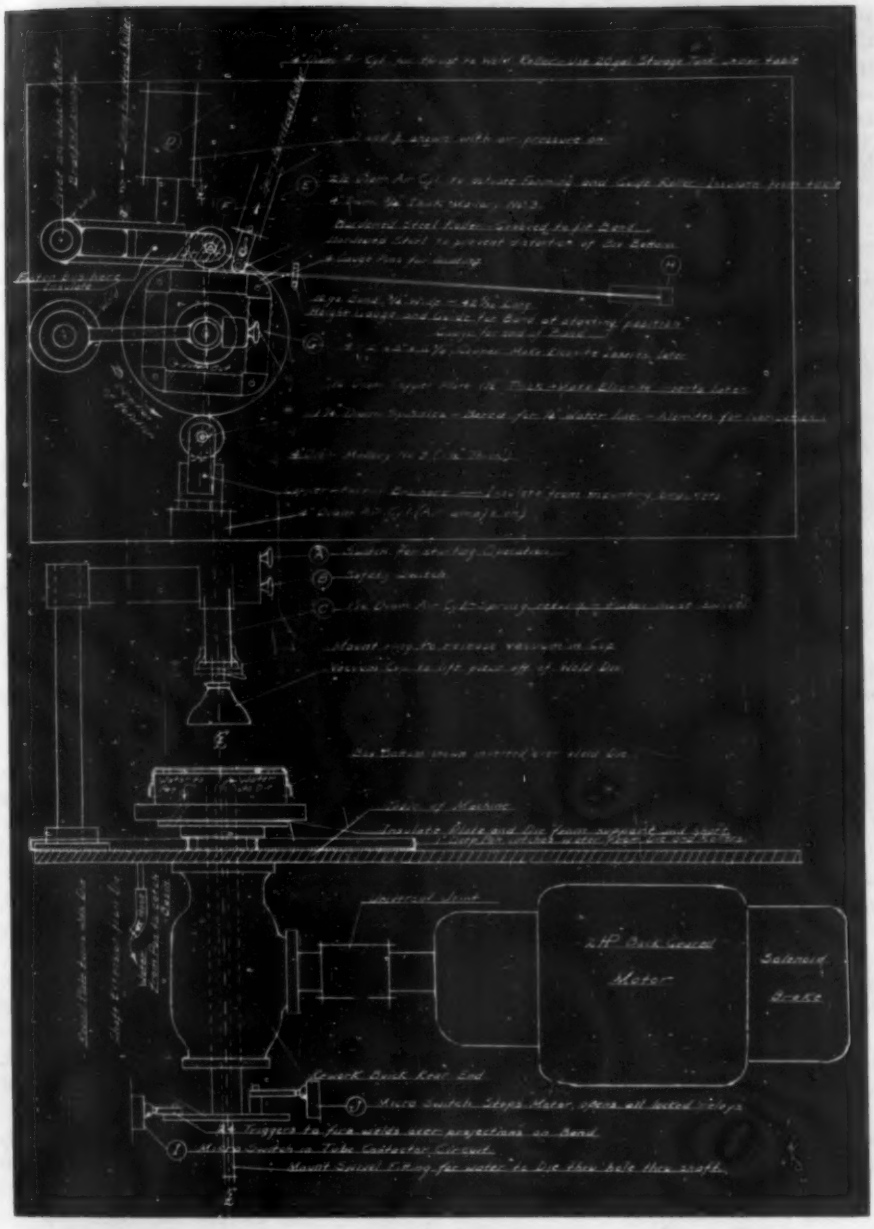

Fig. 1

was connected to the rotating die by using an old Buick rear end and a truck universal joint.

The die itself was of copper with Elkonite inserts at the places where the welds would be made. The die was mounted on a round copper plate about $1^1/_2$ in. thick, also with Elkonite inserts, and a Mallory No. 3 roller, under pressure, rolled

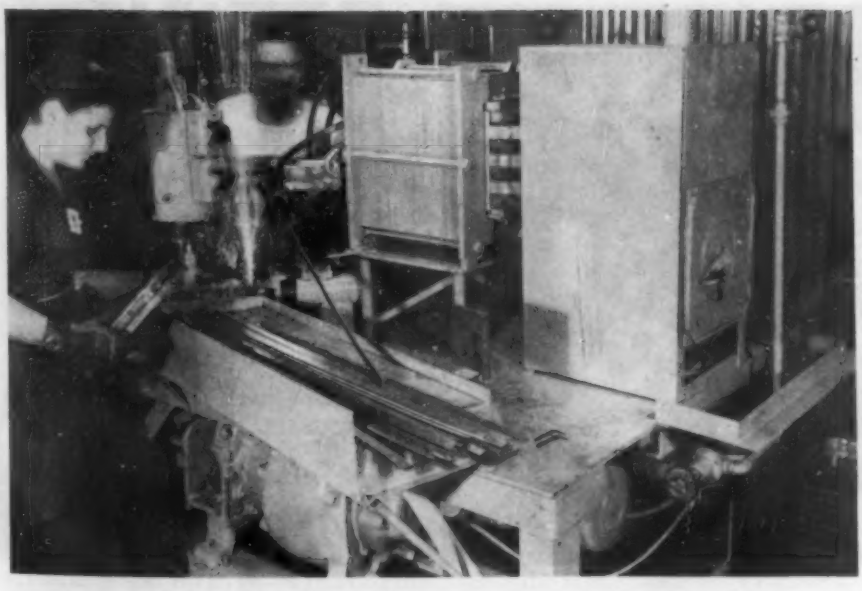

Fig. 2

Fig. 3

against the periphery of this plate to feed the secondary welding current into the die. A laminated bus connected this feed roller to one of the secondary terminals of the welding transformer. The other secondary terminal of the welding transformer was connected by a laminated bus to the weld roller *F* in Fig. 1. This roller was also made of Mallory No. 3. The spindles were made of bronze and were bored for water cooling and grooved for lubrication.

We planned to make one revolution of the die in about 10 sec., and after making that revolution the die would stop dead, due to the action of the solenoid brake on the motor.

An explanation of the operation and the timing sequence for this machine is as follows (refer to Fig. 1):

1. Operator places a box bottom over the die *G*.
2. Operator places one band in the guide, with projections inward, holding it against the box bottom and with the right-hand end of the band against gage *H*.
3. Operator strikes switch button *A* with the left hand. Switch *A* operates a locking relay which locks in a solenoid valve which supplies air cylinder *C*.

This cylinder piston is fitted with a swivel joint and a vacuum cup, and the piston moves downward under the air pressure to hold the box bottom in place on the die and tight against the gage pins on the die corners.

In the air line of this cylinder is a pressure switch which closes when the air pressure builds up. This pressure switch closes the circuit to another solenoid valve which supplies air cylinders *D* and *E*. Cylinder *D* supplies the pressure for the welding roller *F*, which moves in exactly on the end of the band. Cylinder *E* does the forming and guiding of the band ahead of weld roller *F* as the die rotates. Cylinder *E* piston is fitted with a hardened steel roller which is grooved the exact width of the band. This air cylinder and roller are insulated from ground.

In the common air line to cylinders *D* and *E* is another air-pressure switch. When both cylinders *D* and *E* have acted and the air pressure has built up, this pressure switch closes and operates a relay which in turn closes the contactor to the motor, releases the solenoid brake and closes the circuit to the tube contactor of the welding transformer. The tube contactor circuit is also in series with normally open switch *I*, which is ticked on by adjustable triggers mounted on a plate under the table. This plate is on the same shaft as the rotating welding die and turns with it. These triggers are adjusted so that the welding circuit will be closed only at the time weld roller *F* passes over the projections on the band.

Normally closed switch *J* is also mounted under the table and another trigger, which turns with the die, strikes this switch momentarily when the die has made one revolution. This switch and hand-button switch *B*, above the table, are in the circuit of all locking relays. Thus, when the die has made one revolution and the trigger strikes switch *J*, the motor stops, the brake is applied, the weld circuit is broken and all cylinders exhaust and their pistons retract.

As the piston of cylinder *C* retracts, the vacuum cup picks the box bottom off the die and when the cup gets to the top it strikes a pin which releases its vacuum and the welded box bottom drops and is caught in the air by the operator. The operation has been completed.

By striking switch button *B* at any time, the operator can open all circuits. This is purely a safety switch.

One operator with this machine welded 300 assemblies per hour steadily, and the machine operated satisfactorily until the war ended and this assembly line was shut down.

Figure 2 shows the welder in operation. The girl holds in her hands a box bottom which has just had the band welded to it. The projections can be seen on the bands in the tray ready for forming and welding. One band is above the ray in a little holder which positioned the band for quick loading when the cycle of the operation was completed. The two switch controls, *A* and *B*, are visible in the picture, as is the vacuum cup holding the piece down on the die.

An over-all saving of 2.17 man-hours per 100 assemblies was made by the addition of this machine to the line, and it was built at an actual cost of about $1500.

Figure 3 is the finished ammunition box, and Figs. 3, 4, 5 and 6 show some of the other machines we made for this line.

Figure 4 shows a horizontal four-gun projection welder. This machine welded 12 projections at one firing, to

Fig. 4

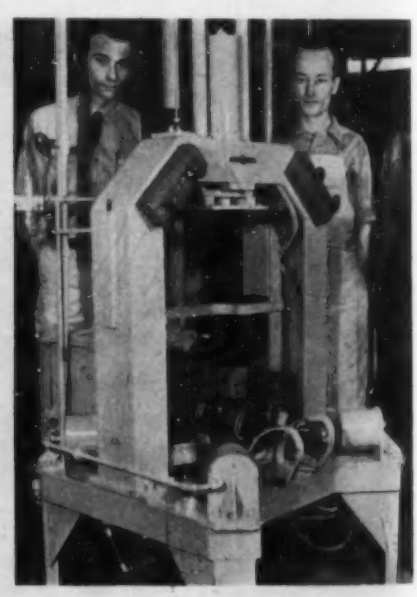

Fig. 5

Fig. 6

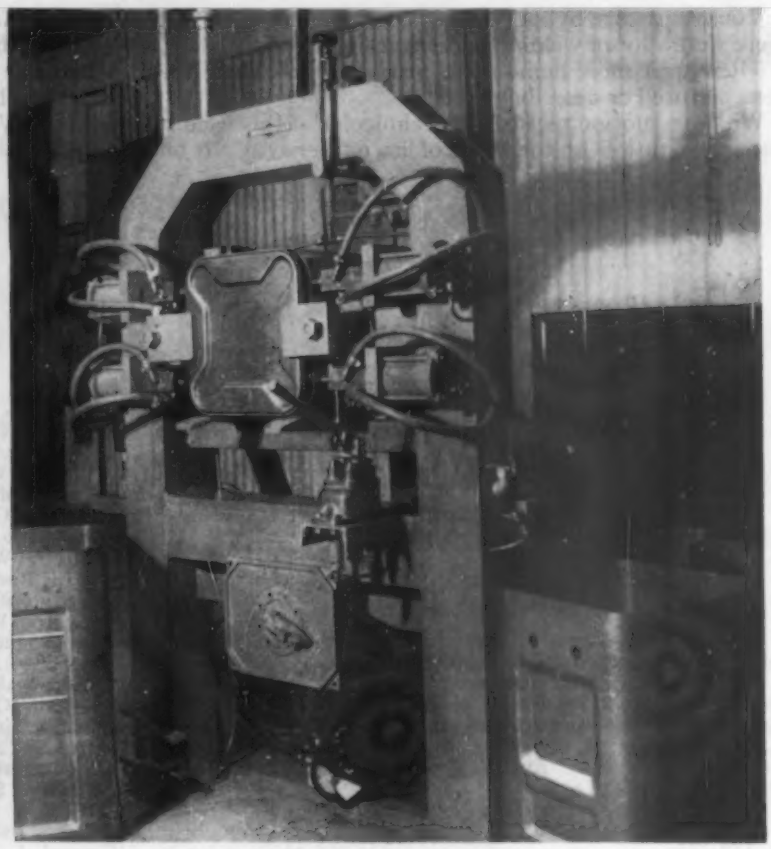

Fig. 7

weld four pieces into a subassembly. Three projections were under each gun. Air-actuated pistons knocked the welded assembly out of the die as the guns retracted after firing. A few finished assemblies are visible on the table at the left side of the figure. Notice the trays for parts, to make the loading operation easy for the operator. One girl operator averaged 250 assemblies per hour on this machine. Formerly, four operators, using jigs and conventional spot welders, were required for this same production rate.

Figure 5 shows a special machine for locating and tack welding a cover-sealing ring just inside the mouth of the box. This ring was later seam welded to the box for watertightness. In operating this machine, the sealing ring was dropped over a die which was then expanded by hitting the lower right button switch. Then the operator inverted an ammunition box and placed it over the ring. He then hit the two top switch buttons. When this was done, an air cylinder pushed the box down over the ring and as the edge of the box bottomed on gages, it struck a limit switch which fired four guns, one on each corner of the box. Then as the guns retracted, the expanded die unlocked and the box was then lifted off the die. The left bottom switch button unlocked the expanding die at any time. Production rate: one operator, 250 boxes per hour. Formerly, six operators were required, using jigs, turntables and welding guns.

Figure 6 shows a 200-kva. Taylor-Winfield seam welder equipped with our fixture for mash seam welding the side seam of the box.

The operator would throw the box body, which had been tack welded, back into the chute. When he stepped on the switch pedal of the machine, the sides of this chute closed up to guide the box and locate the seam under the top wheel. At the same time, the top wheel would come down and as the wheels welded the seam, the box would slide out the chute.

We had a great deal of trouble with the bevel gear drive on the upper wheel of this machine. As the top wheel bearing became worn, the bevel gears would often jam and break. That is why, as you can see in the figure, we removed the bevel gear arrangement and set the drive out at the side of the machine and drove the upper wheel direct. This trouble with the bevel gear drive might well have been due to some neglect or abuse on our part. However, the expedient worked and we certainly decreased the down time of this machine.

Figure 7 is a machine that was used for tack welding the box bottom into the box body. This bottom had previously had the band welded to it as shown in Fig. 2. Later, in a succeeding operation, this bottom was seam welded to the box body for watertightness.

In operating this machine, the operator would slide a seam-welded body into the machine and over a solid weld die. The box body was pushed back against a rigid stop. Then the operator would operate a valve which actuated a cam-operated expanding mechanism which would expand the open end of the box. Then the operator would insert a bottom into the open end of the box and step on a foot pedal. This foot pedal caused the two air-operated clamps, shown in the picture, to revolve and then move in to clamp the bottom into the box against fixed gages. While the operator's foot was still on this pedal, he would operate a Ross valve to bring four welding guns in against the box bottom, two at a time, thus making four welds, two on each side. A pin in the shaft of the clamps moved in a 90° spline cut into a sleeve fastened to the air cylinders. This rotated the clamps out of the way for sliding the box body over the die.

You will realize by looking at the ammunition box that there were a lot of welding operations in making it.

There were more home-made machines, too, than have been pictured or described here.

We have motion pictures in technicolor of this welding line in operation at the peak of its efficiency. No one working with resistance welding could fail to be interested in these films. We were very fortunate in that we had a fine group of employees on this line and the morale was excellent. Each shift tried to out-produce the other. We made nearly 2,000,000 boxes.

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Codes for Arc and Gas Welding in Building Construction*

By L. M. Dalcher†

ACCORDING to Alfred Schindler, Under Secretary of Commerce, there are at the present time more than 2000 different building codes in effect throughout the United States, and more than half of them are at least 20 years old. Mr. Schindler called attention to these facts in a recent article which was published in many of the larger newspapers throughout the country. He pointed out that these obsolete codes restrict the use of new and less costly methods of construction, with the result that the benefits of scientific development are not realized and costs are higher by millions of dollars a year. In concluding his article Mr. Schindler voiced the sentiments of all forward-looking engineers and architects with the statement: "The correction and modernization of these codes is a *must!*"

Realizing the importance of this general problem, particularly as it affects the use of welding in building construction, the AMERICAN WELDING SOCIETY some years ago appointed a committee to prepare a code for fusion welding and gas cutting in building construction. The original committee was composed of eight of the country's leading engineers in the field of structural welding, and their report was adopted and published in 1928 under the title *Code for Fusion Welding and Gas Cutting in Building Construction, Part A—Structural Steel.* Since that time the Code has been revised every few years in order to reflect the latest advances in structural welding. The most recent edition, which was adopted by the Society in April of 1946, bears the title *Standard Code for Arc and Gas Welding in Building Construction.* It will be referred to hereinafter in this article as the Code.

Purpose of Code

Probably at this point it would be well to say something about what this Code is—what it does and what it does not do. Fundamentally it has just one purpose, namely, to give any city or any building commissioner a sound set of rules which can be incorporated in a municipal building code to regulate the use of welding in building construction. Since that is the case, the Code does not serve as a text on structural welding, nor as a technically complete specification for use in a construction contract. It does, however, provide a useful instrument suitable in language, form and coverage for adoption as administrative law for the regulation of welding in building construction.

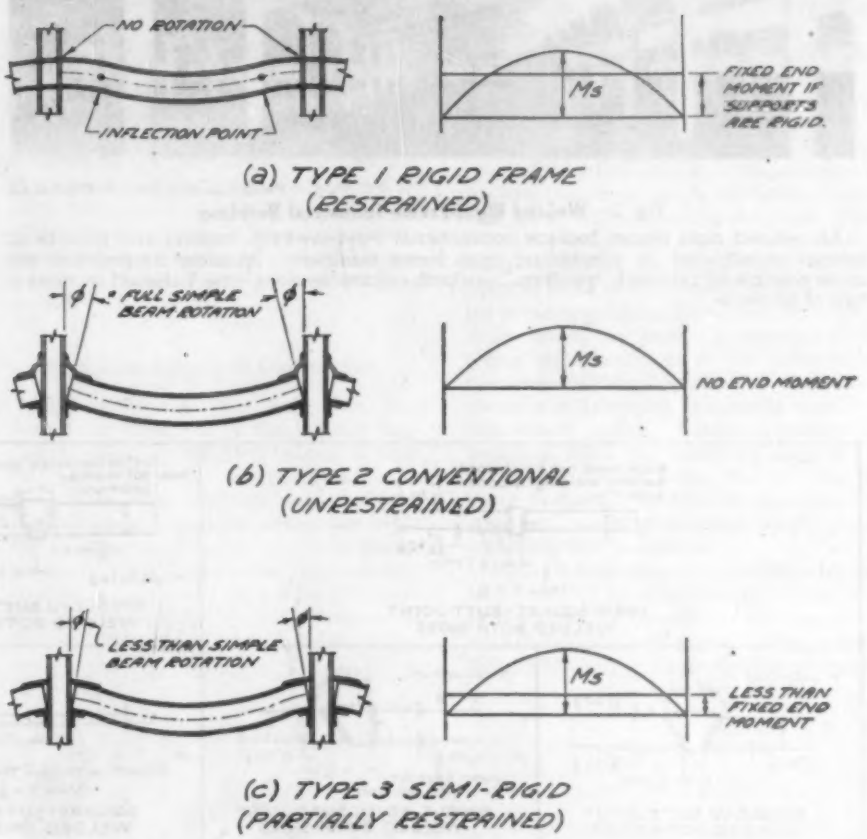


Fig. 1—Three Classifications of Welded Beam-to-Column Connections

Provisions of Code

Since the purpose of the Code is to regulate or control the use of welding, let us see how the Code does it. For purposes of this discussion it is convenient to break the subject down into its two main features: first, the considerations that enter before the actual construction begins; and second, the factors that relate to the actual fabrication and erection of the structure. It is not our intention to discuss either of these aspects completely, or to indicate all of the provisions of the Code. We will, however, discuss some of the more significant provisions as well as the more important changes that have been made since the previous (1941) edition.

Table 1—Permissible Unit Stresses for Welds

Kind of Stress	Permissible Unit Stress, Psi.
Tension on section through throat of butt weld	Same as corresponding allowable stress for base metal
Compression on section through throat of butt weld	Same as corresponding allowable stress for base metal
Shear on section through throat of butt weld	Same as corresponding allowable stress for base metal
Shear on section through throat of fillet weld, or on faying surface area of plug or slot weld	13,600

* Based on a paper presented by the author at a meeting of the Louisville Section of the AMERICAN WELDING SOCIETY in Louisville, Ky., on April 23, 1946.

† Technical Secretary, AMERICAN WELDING SOCIETY, New York, N.Y.

Photo Courtesy Lincoln Electric Co.

Fig. 2—Welded Rigid-Frame Industrial Building

Arc-welded rigid frames replace conventional truss sawtooth framing and provide an interior unrestricted by intervening cross frame members. Trussless construction was made possible by pronged "tree-form" sawtooth column sections—the Y-shaped sections at tops of columns.

Pre-Construction Provisions

The pre-construction provisions of the Code relate to those factors with which the planning and designing engineers are concerned. One example is the establishment of permissible types of construction, based on a systematic classification of the various practices with respect to design assumptions. The Code provides for the use of any of three basic types of design and design assumption, namely: (1) rigid-frame; (2) conventional or simple framing; and (3) semi-rigid framing. These different types of construction are illustrated schematically in Fig. 1 and are defined in the Code as follows:

"Type 1, commonly designated as 'rigid-frame' (continuous, restrained), assumes that the end connections of beams, girders and all other members in the frame have sufficient rigidity to hold virtually unchanged the original angles between such members and the members to which they connect.

"Type 2, commonly designated as 'conventional' or 'simple' framing (unrestrained, free-ended), assumes that the ends of beams and girders are connected for shear only, and are free to rotate under load.

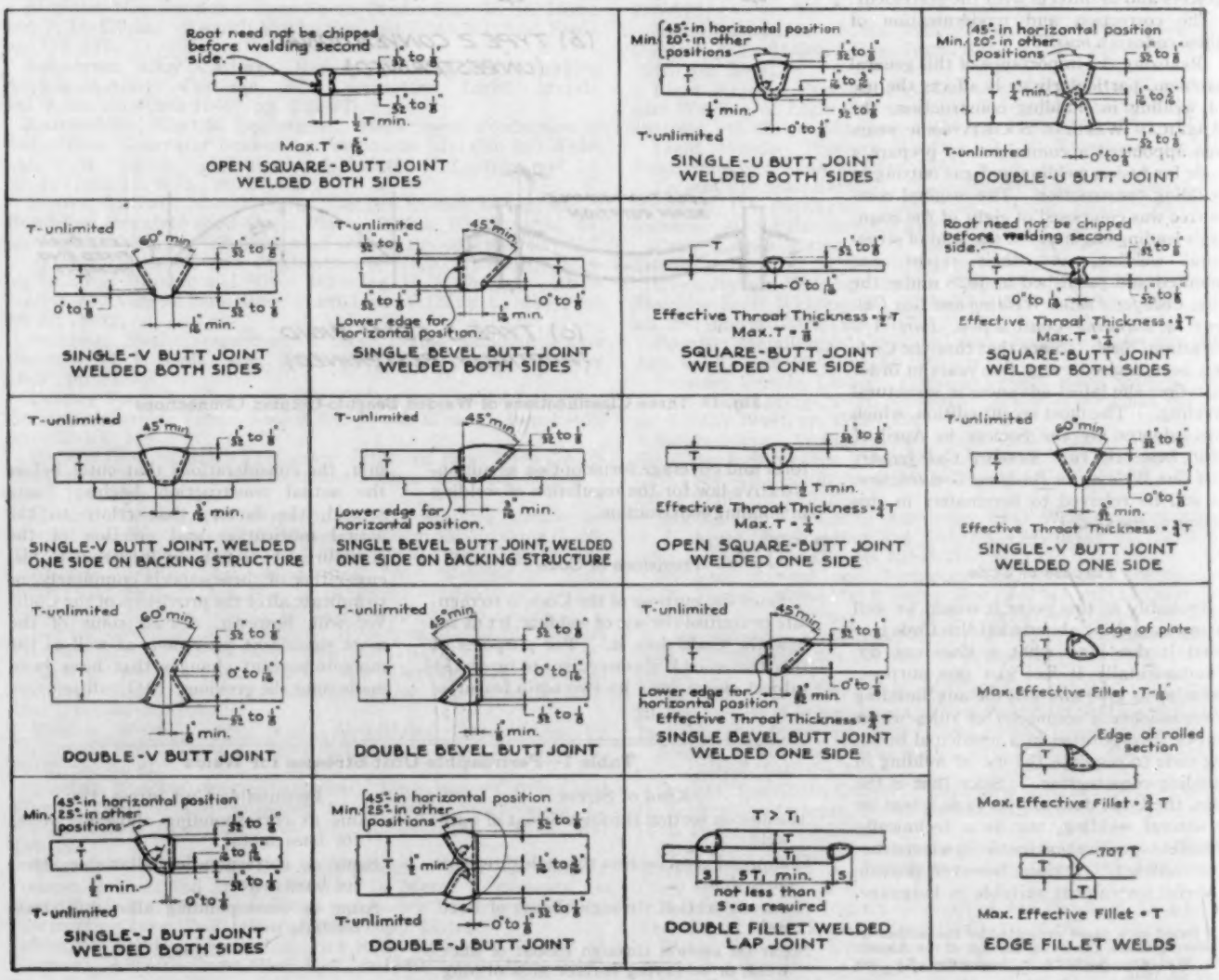

OPEN SQUARE-BUTT JOINT WELDED BOTH SIDES
SINGLE-U BUTT JOINT WELDED BOTH SIDES
DOUBLE-U BUTT JOINT
SINGLE-V BUTT JOINT WELDED BOTH SIDES
SINGLE BEVEL BUTT JOINT WELDED BOTH SIDES
SQUARE-BUTT JOINT WELDED ONE SIDE
SQUARE-BUTT JOINT WELDED BOTH SIDES
SINGLE-V BUTT JOINT, WELDED ONE SIDE ON BACKING STRUCTURE
SINGLE BEVEL BUTT JOINT, WELDED ONE SIDE ON BACKING STRUCTURE
OPEN SQUARE-BUTT JOINT WELDED ONE SIDE
SINGLE-V BUTT JOINT WELDED ONE SIDE
DOUBLE-V BUTT JOINT
DOUBLE BEVEL BUTT JOINT
SINGLE BEVEL BUTT JOINT WELDED ONE SIDE
SINGLE-J BUTT JOINT WELDED BOTH SIDES
DOUBLE-J BUTT JOINT
DOUBLE FILLET WELDED LAP JOINT
EDGE FILLET WELDS

Fig. 3—Standard Details of Welded Joints for Building Construction

"Type 3, commonly designated as 'semi-rigid framing' (partially restrained), assumes that the connections of beams and girder possess a dependable and known moment capacity intermediate in degree between the complete rigidity of Type 1 and the complete flexibility of Type 2."

Rigid-frame design is particularly adapted to welded construction, since it takes full advantage of the inherent rigidity of welded connections. Figure 2 shows a good example of the application of rigid-frame design to an industrial building. It will be noted that this modern type of construction results in improved appearance, and that the elimination of trusses has provided improved lighting and greater head room, as well as a structure that is much simpler to clean, paint and maintain.

One of the most important features of the Code—and one that seems to be of particular interest to most Building Commissioners—is the permissible unit stresses for welds. These are shown in Table 1. It should be pointed out that the values given in this table are for welds made with base metal conforming to A.S.T.M. Specification A7, *Structural Steel for Bridges and Buildings*, and filler metal conforming to certain classifications* established in A.W.S.-A.S.T.M. Specifications A233, *Iron and Steel Arc Welding Electrodes*, and A251, *Iron and Steel Gas Welding Rods*.

Table 1 is of interest also from the standpoint that it embodies the most significant change from the previous (1941) edition of the Code. In the 1941 edition the value ascribed to butt welds in tension was 16,000 psi., whereas it is now the same as the corresponding allowable stress for the base metal. This increase in unit stress is amply justified by the results of numerous tests, both static and dynamic, and by the results of experience over a period of many years. It might also be pointed out that a similar change has been made in the latest edition of the A.I.S.C. *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings*. The latter specification prescribes an allowable unit stress in tension of 20,000 psi. for structural steel and 20,000 psi. for butt welds.

Perhaps the most interesting feature of the code is its provisions for qualifying welding procedures. Many of the recognized welding codes and specifications require the contractor to prepare certain test plates using the welding procedure intended to be used in the subsequent fabrication work. These test plates are then subjected to a number of tests (usually for tensile strength, soundness and ductility) and the governing code or specification states what requirements the test plates must meet in order that the welding procedure may be considered qualified, that is, approved for use in the particular application.

While the foregoing procedure is sound in principle, the A.W.S. Committee on Building Codes has recognized the fact that there are a number of commonly accepted welding procedures that have been used successfully time and again in welding structural steel. Furthermore, it has been demonstrated by means of countless tests that these procedures do yield results that will meet or exceed the requirements of the standard qualification tests. For that reason the Committee established certain joint designs and welding procedures, and set forth in the Code that any contractor might use these procedures without having to conduct procedure qualification tests. The joint designs thus exempted from qualification requirements ("prequalified") are shown in Fig. 3.

Anyone who has had experience with welding procedure qualification tests will readily appreciate that these prequalified procedures will save the contractor a great deal of time and expense. On the other hand, the Committee realizes that these are not the only procedures that may be used, and that new procedures, equal or superior to the prequalified ones, may be developed in the future. For that reason the Code prescribes that such new or different procedures shall be tested and qualified in accordance with the A.W.S. *Standard Qualification Procedure*. When so qualified, they can be used under the Code and enjoy the same status as the prequalified procedures.

Provisions Relating to Construction

The factor that has just been discussed—qualification of the welding procedure—may be regarded as one of four controls which taken together ensure the production of satisfactory welds. These controls are necessary for almost any welding application, whether in shipbuilding, pressure vessel construction, aircraft fabrication, or any other type of construction in which the quality of the welding is important. These four controls are listed below:

1. Qualification of the welding procedure.
2. Qualification of the welding operator.
3. Supervision during welding.
4. Inspection.

The last three items all relate to the actual fabrication and erection of the structure, and are covered by specific provisions of the Code.

With regard to qualification of welding operators, the Code specifies that they "shall be previously qualified by tests as prescribed in the AMERICAN WELDING SOCIETY'S *Standard Qualification Procedure* or by such other tests as the Building Commissioner may prescribe."

Figure 4 illustrates one of the provisions of the Code relative to inspection of the welding in progress. It is prescribed that the inspector shall occasionally observe the technique and performance of the welding operators, to determine that the prescribed welding procedures are being followed and that sound welds are being obtained. The frequency of such observations must necessarily be left to the judgment of the inspector, since it will depend upon a number of factors peculiar to the particular job. If the welds are such that strength is of minor importance, or if the work of a particular welding operator has been consistently satisfactory, occasional observation should suffice. Closer inspection is indicated when the welds are located at important points, when the welding is being performed in difficult positions, or when the welding operator must work under physical handicaps.

Figure 5 illustrates the provisions of the Code relative to weld profiles. These details are readily checked by the inspector with the aid of a weld gage. A more serious defect than any of those illustrated would

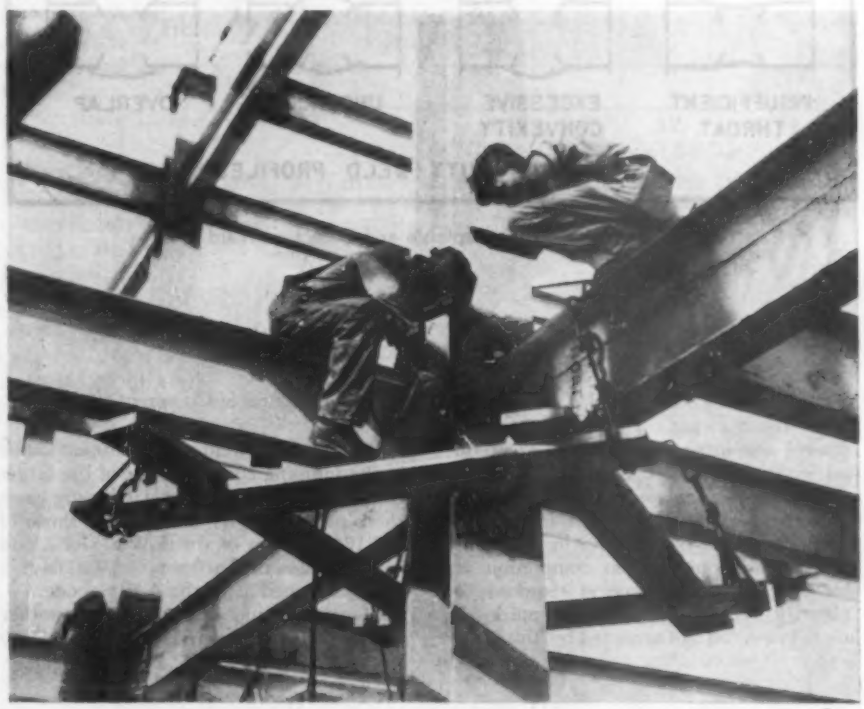


Photo Courtesy Air Reduction

Fig. 4—Scene During Erection of All-Welded Kentucky State Office Building, Frankfort, Ky., Showing Simple Scaffolding Required

* For arc welding electrodes: classifications E6010, E6011, E6012, E6013, E6020 or E6030; for gas welding rods: classifications GA60 or GA65.

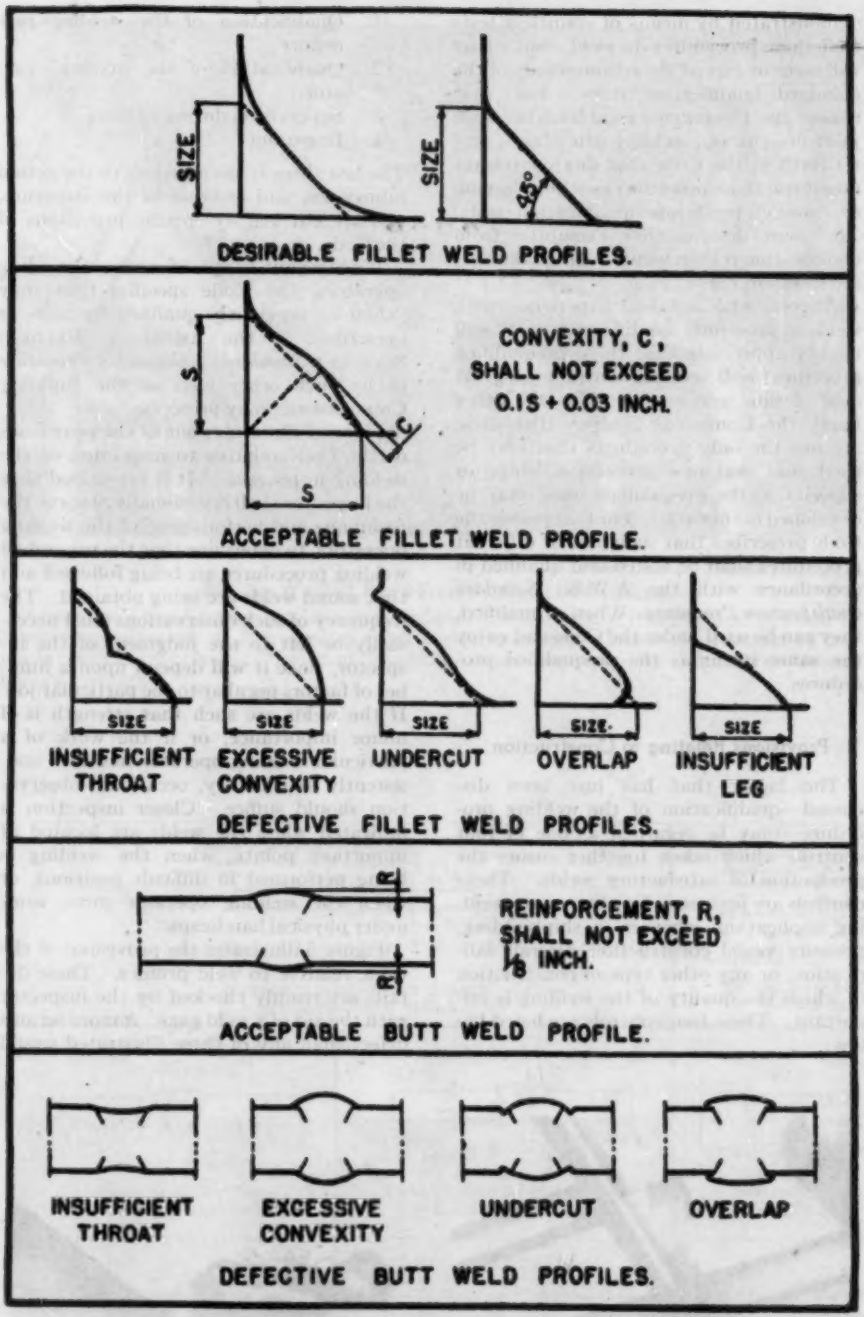


Fig. 5—Illustration of Acceptable and Defective Weld Profiles

be the complete omission of a weld called for on the drawing. The Code therefore requires the inspector to make a careful and systematic check to insure that no welds have been omitted, that all welds are of the proper size and length and in the proper locations as called for in the plans and specifications. Upon completion of this check the inspector is required to "identify with a distinguishing mark all points inspected and accepted by him."

Adoption of Code by Cities

Provisions for welding are now embodied in the building codes of most of the larger cities in the United States. In many cases these provisions are identical to those of the 1941 edition of the A.W.S. Code, and in other cases they are very similar, having been patterned after the A.W.S. code.

Mention should also be made of another way in which the provisions of the Code have found their way into hundreds of municipal building codes. This was the result of the incorporation of the A.W.S. Code in the standard building codes developed by other organizations. For example, the A.W.S. Code is incorporated in large part in the 1946 edition of the *Uniform Building Code*, prepared by the Pacific Coast Building Officials Conference. The latter code has been adopted by more than 400 cities and towns in 35 states (including many large cities such as Birmingham, San Diego, Denver, New Orleans, Dallas and Houston), by several counties, and by the States of Indiana and New Mexico. The A.W.S. Code has similarly been incorporated in large part in the *American Standard Building Code Requirements for Structural Steel*, issued by the American Standards Association, and in the *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings*, issued by the American Institute of Steel Construction.

Action by A.W.S. Local Sections

Many of the district chapters of the AMERICAN WELDING SOCIETY have been active in assisting their local building commissioners in drawing up suitable regulations for the use of welding in building construction. In Cleveland, for example, the chairman of the Cleveland Section appointed a Code Committee to prepare suitable recommendations. That committee held several meetings to which were invited representatives from the American Institute of Architects, the National Society of Professional Engineers and the American Institute of Steel Construction. As the result of these meetings, all four groups agreed to recommend to William Guion, Building Commissioner, the provisions embodied in the 1946 edition of the A.I.S.C. *Specification for the Design Fabrication and Erection of Structural Steel for Buildings**. Mr. Guion has assured the Code Committee that he will be guided by their recommendations in preparing the new Cleveland Code, and that in the meantime the Department of Buildings will approve construction in accordance with the A.I.S.C. Specification.

It is gratifying to note that at the present time a large number of cities are engaged in revising their building codes. Public interest in these projects is unusually high, due to the fact that building construction is now a problem of immense national importance. These circumstances have created for the engineer and architect a splendid opportunity—an opportunity which is at the same time an obligation—to use their influence to see that these revisions result in building codes that are truly up to date. Especially is it important that these codes make adequate provision for the modern methods of construction that have resulted from recent scientific developments.

* As stated previously, the 1946 edition of the A.W.S. *Standard Code for Arc and Gas Welding in Building Construction* is largely incorporated in the A.I.S.C. Specification.

Variation in Quality of Spot Welds in Low-Carbon Steel Over a Range of Welding Variables

By J. J. Riley*

Introductory Summary

LOW CARBON steel is so readily weldable that it is often used as a standard for judging the weldability of other steels and metals. Moreover, the ease of welding permits the selection of numerous combinations of welding variables. These combinations do not make identical welds. Some deviations in physical properties and appearance and in metallurgical structure result. Regardless of these differences if any combination reproduces uniform welds, it is feasible to judge weld quality from the combination of welding variables or setup used in making the weld.

From hundreds of welds made with different welding setups, it is demonstrated that weld quality can be definitely predicted from the setup. Three basic types of setups were selected as representing the range of spot welding conditions in industrial production.

Short weld time, high electrode force and high welding current results in Class A or best welds. Medium weld time, medium electrode force and medium welding current results in Class B or medium welds. Long weld time, low electrode force and low welding current results in Class C or good welds.

Comparison of weld characteristics or quality of Class A through Class C welds discloses that the average shear strength decreases, the spread between maximum and minimum shear strength increases, the degree of porosity increases and the percentage of welds likely to fail by tearing slugs from the metal decreases. Other characteristics such as surface indentation and sheet separation remain essentially constant. All classes of welds are reliable and show symmetrical nugget formation, adequate penetration, no unusual surface marking and predictable shear strength.

Foreword

The effect of welding variables on weld heating is expressed by the equation

$$H = I^2Rt + \text{losses} = I^2Rwt$$

where

H = heat for the welding operation
I = welding current
t = time of current flow

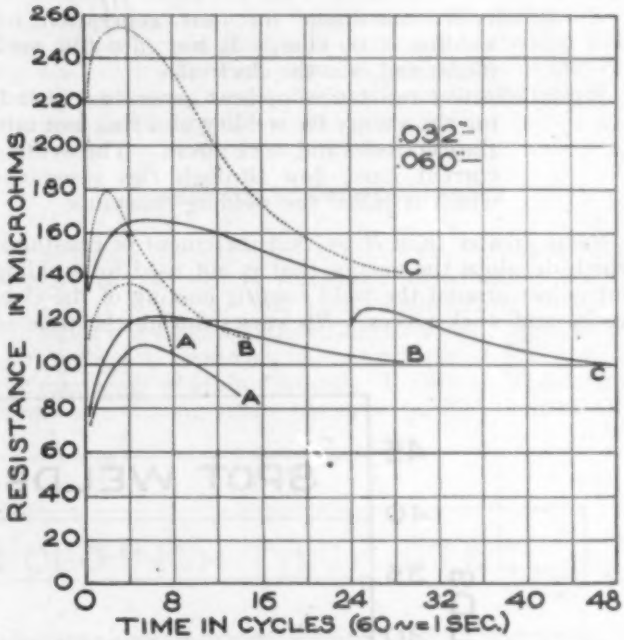


Fig. 1—Variation of Welding Resistance with Time During Welding for 0.032-In. Thick and 0.060-In. Thick Low-Carbon Steel Sheet

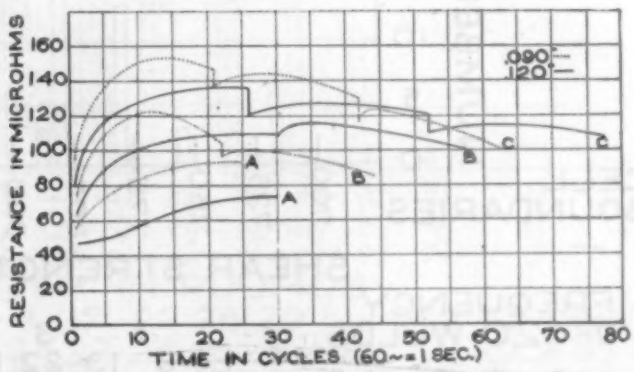


Fig. 2—Variation of Welding Resistance with Time During Welding for 0.090-In. Thick and 0.120-In. Thick Low-Carbon Steel Sheet

* Sales Engineer, The Taylor-Winfield Corp., Warren, Ohio.

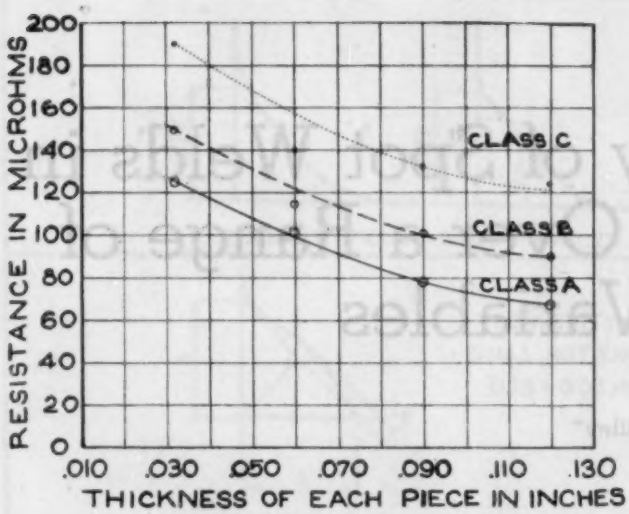


Fig. 3—Variation of the Average Welding Resistance with Thickness for Low-Carbon Steel Sheet

R = effective resistance for heat generation for welding if no energy is lost into the work pieces and into the electrodes

Rw = effective resistance for heat generation including the energy for welding and that lost into the electrodes and work pieces. The welding current must flow through this resistance which is called the welding resistance

Rw is greater than R by that increment of resistance which develops the energy that is not used for welding but is lost around the weld causing heating of the electrodes and work pieces. Rw varies during the time of current flow in making a weld and for purposes of calculation an average value is selected.

The variables in the basic equation are dependent on each other as well as on other variables necessary for a welding setup. The value of the welding current I is related to the electrode face diameter, the electrode force, the time of current flow and the thickness of the steel. Both R and the welding resistance, Rw, are functions of the surface preparation of the steel sheets, of the resistivity of the metal, of the welding current (in relation to electrode face area), of the electrode force (in relation to electrode face area) and of the thickness of the steel sheets. The time, t, is a function of the welding current, the welding resistance and the thickness of the steel sheets. The heat, H, is dependent on the thickness of the steel sheets and the time of welding. Longer welding times require more total heat generation because of the increased losses.

The usual limiting factor of most spot welders is the maximum available electrode force. The importance of electrode force on the welding setup is obvious from the preceding discussion of variables. For these reasons the electrode force was chosen as the principal welding variable governing the selection of setup. The other main variables, welding current and time of current flow, were then adjusted until the most satisfactory weld was made. The value of welding current was made as large as possible without causing spitting or expulsion of metal. The time of current flow was based on obtaining adequate penetration and nugget diameter. The proper time of current flow should produce a nugget diameter nearly equal to the electrode face diameter.

A spot weld has many characteristics which can be employed to judge weld quality. The importance of these characteristics depends on the welding application. As an arbitrary general case the spot weld will be considered

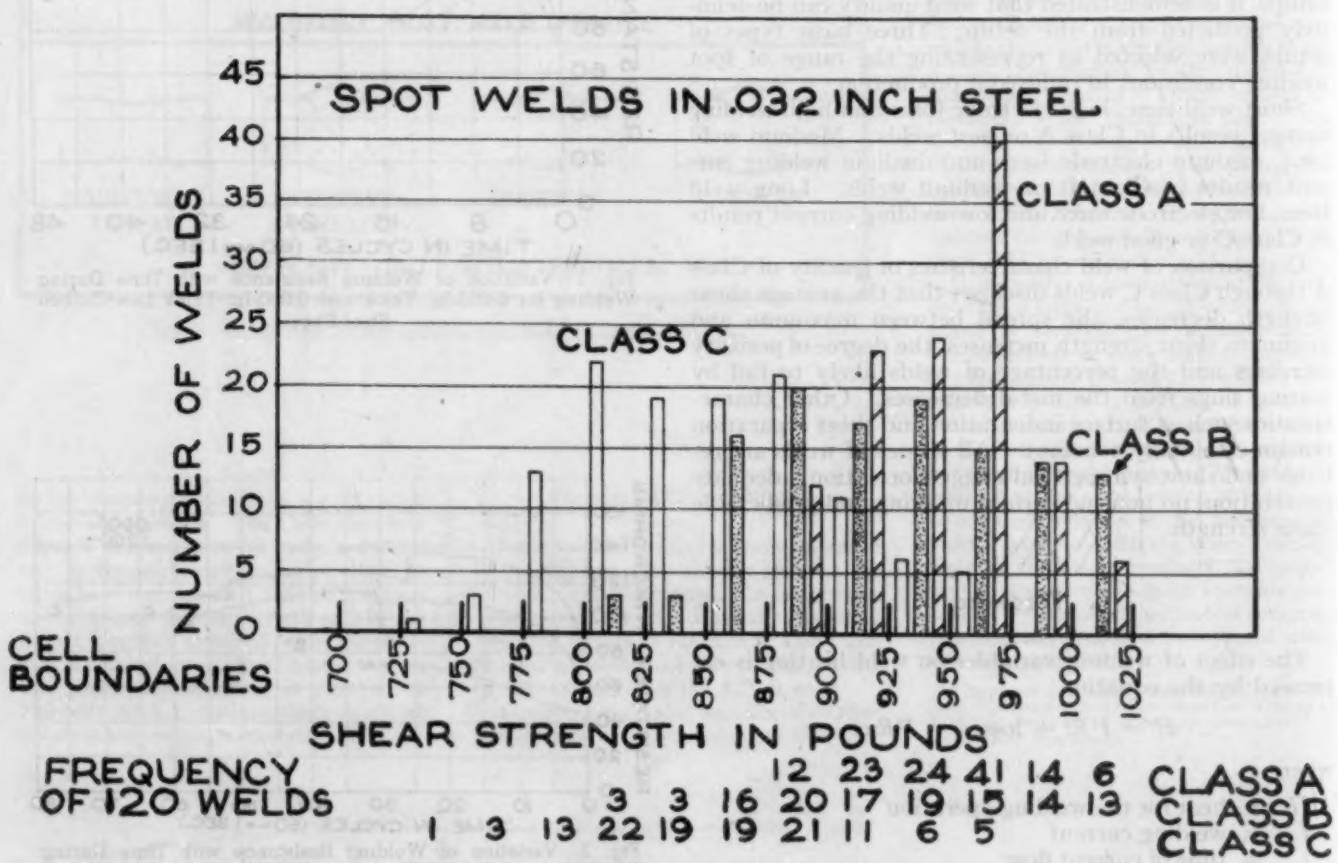


Fig. 4—Frequency Distribution of Shear Strengths

a superior substitute for a rivet in which the weld is subjected to a comparatively nonrepetitive type of shear loading. In such a case the product designer is concerned about: the average shear strength, the diversity or range of shear strength with the same welding conditions, the type of failure so that an overstressed part shows parent metal rather than weld metal failure, the surface marking and indentation and the degree of heat dissipation into the component parts producing distortion. The metallurgical structure is of secondary importance as long as the physical test values are maintained.

Procedure

The spot welding was carried out under controlled conditions which could easily be duplicated in production. The weld timing was accurately controlled by a synchronous timer. The electrodes were dressed only once in a series of welds in any specific thickness. The initial dressing was necessary to establish good electrode contact over the entire face. The steel being welded was of commercial low-carbon grade, hot rolled, pickled and oiled. It was slightly rimmed. Its ultimate tensile strength varied between 42,000 and 45,000 psi. Before welding the dirt was wiped from the sheet. After wiping, the sheet was perceptibly oily.

The electrode force was set such that the electrode pressure (quotient of the electrode force divided by the electrode face area) was approximately 5000 psi. for Class C welds; 10,000 psi. for Class B welds and 16,000 psi. for Class A welds. The forces recommended by the AMERICAN WELDING SOCIETY were used for Class A welds. For each setting of electrode force and steel thickness a run of approximately 135 welds was made. After every 20 welds, one weld was selected for metallurgical sectioning and etching. A multiple weld specimen was made for each welding setup to determine the degree of current shunting between welds.

The energy for welding was calculated by multiplying the square of the current by the welding resistance and the time of current flow. The welding resistance is the resistance between the electrodes across the work pieces. It was determined by measuring the voltage drop across the electrodes and the welding current by means of an oscillograph. The voltage drop divided by the current gave the resistance. Values of resistance were calculated for each half cycle. The results are shown in Figs. 1 and 2. The variation of the average welding resistance with thickness is indicated in Fig. 3. The oily surface of the sheets caused a larger value of welding resistance than would be expected from degreased sheets.

It was felt that sufficient information could be gathered for a general analysis if the welding investigation was confined to thicknesses of 0.032, 0.060, 0.090 and 0.120 in. The welding setups for these thicknesses are listed in Table 1. The tensile shear coupon sizes were: 1 x 4 in. for 0.032-in. thick steel; $1^1/_2$ x 5 in. for both 0.060- and 0.090-in. thick steel; and 2 x 6 in. for 0.120-in. thick steel.

Throughout this work the weld timing was meant to be primarily single impulse, but the welder control used would not pass impulses longer than 30 cycles or $^1/_2$ sec. When longer times were necessary, pulsation timing was used. In these cases equal lengths of current impulses were set using the minimum cool time of 3 cycles as limited by the sequence weld timer.

Presentation of Data and Results

The tensile shear strength loads for the various welding setups are plotted as frequency distribution charts, Figs. 4, 5, 6 and 7. All load values falling within a cell block are assumed equivalent to a load, equal to the cell mid-point, occurring as many times (frequency) as the number of welds in that cell. For the welds resulting from each welding setup, the average, $\bar{X}$; the standard

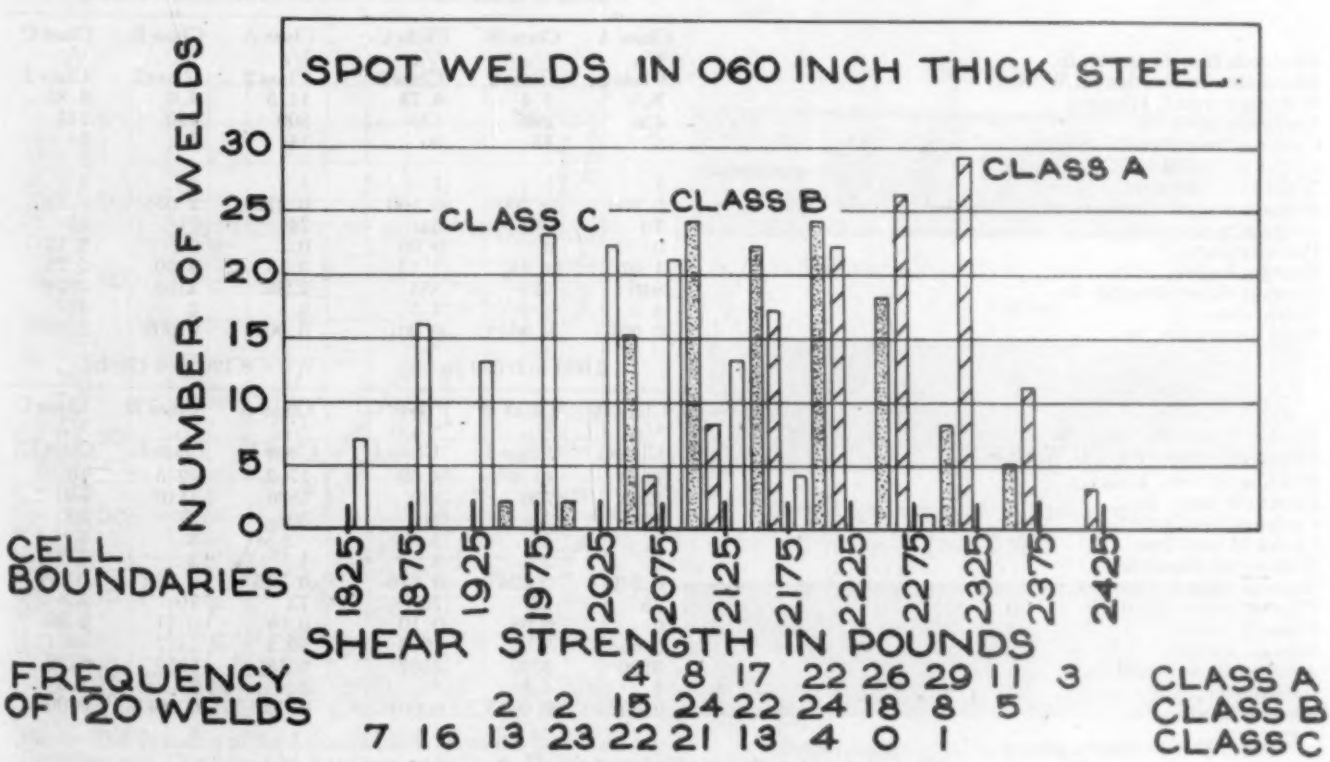


Fig. 5—Frequency Distribution of Shear Strengths

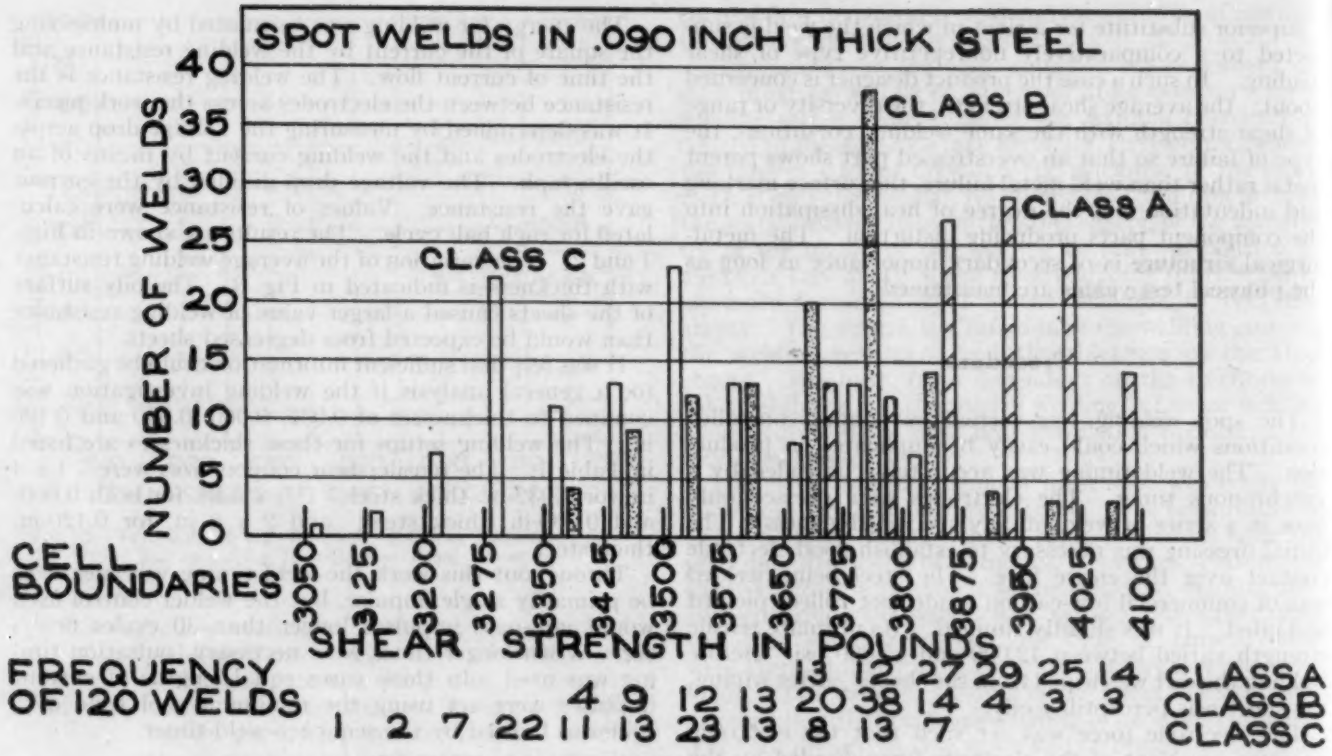


Fig. 6—Frequency Distribution of Shear Strengths

deviation, σ; and the coefficient of variation, v, are calculated in accordance with the procedure suggested by the American Society for Testing Materials.[2] These values which are indicative of the scatter pattern of loads from the average load are compared with stock thickness in Fig. 8. In comparing two welding setups resulting in equal average load values, the scatter of actual loads from the average value will be greater in the setup with the larger standard deviation factor and coefficient of variation.

Table 1—Welding Setups and Physical Characteristics of Welds

	0.032 to 0.032 In.			0.060 to 0.060 In.		
	Class A	Class B	Class C	Class A	Class B	Class C
Electrode face diameter, in.	3/16	3/16	3/16	1/4	1/4	1/4
Electrode composition, R.W.M.A.	Class 2	Class 2	Class 2	Class 2	Class 2	Class 2
Welding current, kiloamp.	8.0	6.4	4.73	11.5	9.0	6.85
Electrode force, lb.	425	280	135	800	490	245
Cycles of heat time*	8	15	30	14	29	24
Cycles of cool time	....	....	....	....	....	3
Number of impulses	1	1	1	1	1	2
Average nugget diameter, in.	0.206	0.200	0.160	0.272	2.055	0.245
Average penetration, %	70	78	55	74	71	65
Porosity factor†	0	0	0.05	0	0	0.12
Energy, kw.-sec.	1.07	1.48	2.12	3.14	4.50	5.25
Average shear strength, lb.	946	926	885	2235	2165	2024
Indentation, %	4.5	4.5	4.5	3	3	3
Sheet separation, in.	0.001	0.001	0.001	0.002	0.002	0.0015
	0.090 to 0.090 In.			0.120 to 0.120 In.		
	Class A	Class B	Class C	Class A	Class B	Class C
Electrode face diameter, in.	5/16	5/16	5/16	3/8	3/8	3/8
Electrode composition, R.W.M.A.	Class I	Class I	Class I	Class I	Class I	Class I
Welding current, kiloamp.	14.3	11.4	8.52	17.2	12.8	10.0
Electrode force, lb.	1250	770	380	1800	1110	550
Cycles of heat time*	25	21	21	30	27	26
Cycles of cool time	....	3	3	....	3	3
Number of impulses	1	2	3	1	2	3
Average nugget diameter, in.	0.340	0.324	0.316	0.395	0.386	0.372
Average penetration, %	75	73	70	73	70	65
Porosity factor†	0	0.08	0.10	0.08	0.11	0.25
Energy, kw.-sec.	6.65	8.92	10.3	10.1	14.7	16.4
Average shear strength, lb.	3890	3702	3507	6518	6250	6129
Indentation, %	4	4.8	3	3	3	1.5
Sheet separation, in.	0.002	0.0015	0.001	0.002	0.0015	0.002

* Based on 60 cycle frequency.
† See paragraph 3 of Presentation of Data for explanation of this factor.

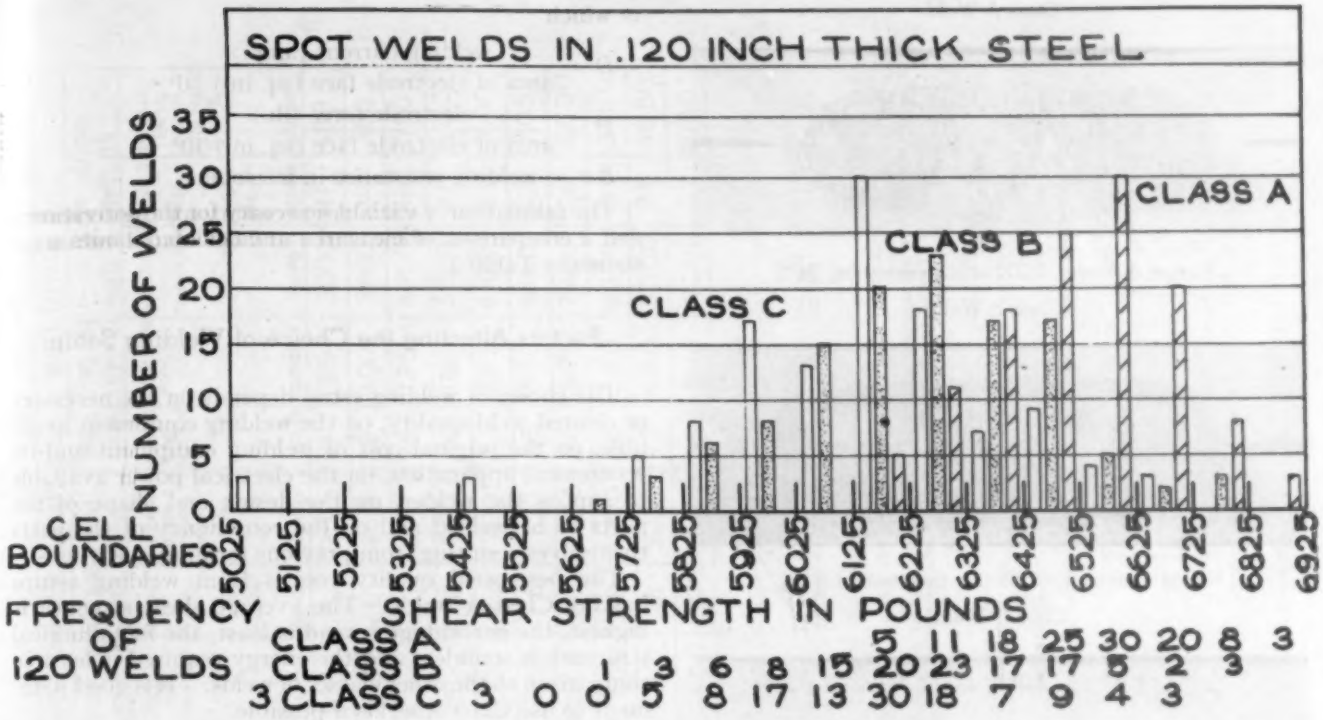

SPOT WELDS IN .120 INCH THICK STEEL
NUMBER OF WELDS
CLASS A
CLASS B
CLASS C
CELL BOUNDARIES
FREQUENCY OF 120 WELDS
SHEAR STRENGTH IN POUNDS
CLASS A 5 11 18 25 30 20 8 3
CLASS B 1 3 6 8 15 20 23 17 17 5 2 3
CLASS C 3 3 0 0 5 8 17 13 30 18 7 9 4 3

Fig. 7—Frequency Distribution of Shear Strengths

The welding was performed under physically controlled conditions on the same type of material and the frequency distribution curve, for all practical purposes, can be assumed to be defined by the Normal Law. The results justified this assumption. On this basis the maximum and minimum tensile shear strengths were calculated from the average strength by adding and subtracting an increment of pounds equal to three times the standard deviation factor, see Appendix A.

Some welding setups made porous welds. If a weld is sectioned through the middle and etched, it is simple to estimate the defective portion of the exposed area. Often in the reproduction of photomacrographs the definition and contrast in the weld nugget is so poor that porosity is difficult to judge. Consequently, a porosity rating has been devised which expresses the ratio of length of defect of the weld nugget to the total nugget diameter. These measurements are made in the same plane.

The differences in metallurgical structure of the welds between the various classes of welds were not studied in

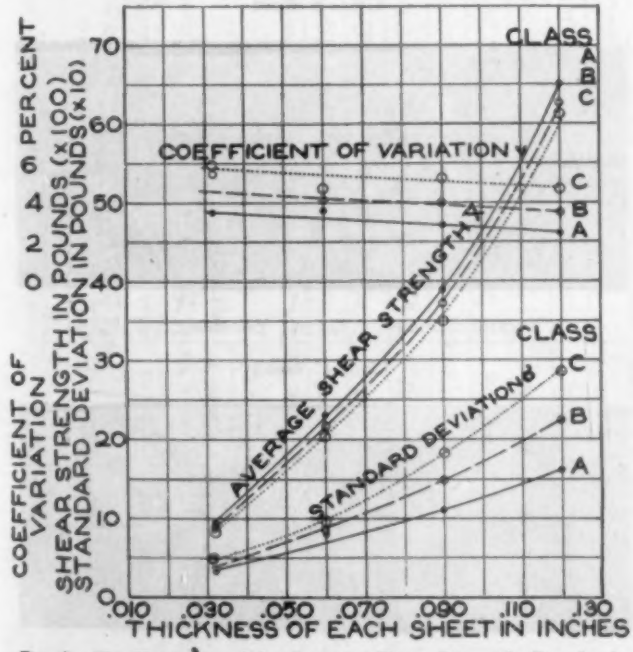


Fig. 8—The Variation of the Average Shear Strength, Standard Deviation and Coefficient of Variation with Stock Thickness for Low-Carbon Steel

Class A Weld

Nugget diameter, 0.206 in.; penetration, 70%

Class B Weld

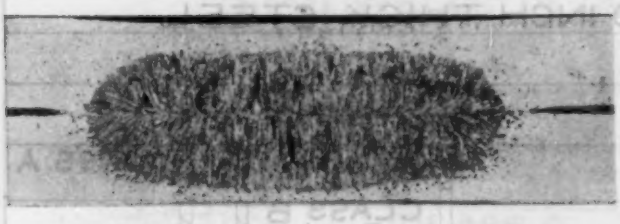
Nugget diameter, 0.200 in.; penetration, 78%

Class C Weld

Nugget diameter, 0.160 in.; penetration, 55%

Fig. 9—Photomacrographs of Welds in 0.032-In. Thickness

Class A Weld



Nugget diameter, 0.272 in.; penetration, 74%

Class B Weld

Nugget diameter, 0.255 in.; penetration, 71%

Class C Weld

Nugget diameter, 0.245 in.; penetration, 65%

Fig. 10—Photomacrographs of Welds in 0.060-In. Thickness

detail. The steel before welding was spheroidized annealed. After welding there was more evidence of carbon migration from the carbides in long-time welds than in short-time welds. Photomacrographs of typical welds in all classes are shown in Figs. 9, 10, 11 and 12.

The general group of Class C welds was more likely to fail through the faying surfaces at the weld than tearing metal around the weld. Considering the 120 welds of each class and thickness which were subjected to shear loading, there were no faying surface failures in Class A welds. The Class B welds in 0.032-in. stock resulted in 11 faying surface failures. Class B welds in other gages all were button type failures. Class C welds failed at the faying surfaces as follows: 65 in 0.032-in., 1 in 0.060-in., 8 in 0.090-in. and 10 in 0.120-in. thick steel. The strength values of faying surface failures were of equal value to button type failures.

The variations of welding current, electrode force and welding time with stock thickness are shown in Fig. 13. From these relationships and the previous knowledge of weld strengths, the master chart for the spot welding of low-carbon steel was compiled, Table 2.

The energy necessary for welding a specific thickness is a distinct function of the welding setup as is clearly shown in Fig. 14. The measurement of welding resistance needed for the energy calculations provided data to attempt a derivation of an empirical formula, applicable to low-carbon steel with flat electrodes, which relates indirectly the effect of welding current and electrode force on welding resistance. The formula, is

$$Rw = \frac{333(D^{1.5} + 1.7)}{P + 2}$$

in which

$$D = \frac{\text{welding current (amp.)}}{\text{area of electrode face (sq. in.)}\ 10^5}$$

$$P = \frac{\text{electrode force (lb.)}}{\text{area of electrode face (sq. in.)}\ 10^3}$$

Rw = welding resistance in microhms

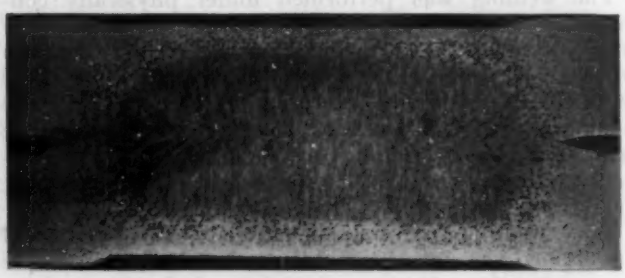
The tabulation of variables necessary for the derivation and a comparison of measured and calculated values are shown in Table 3.

Factors Affecting the Choice of Welding Setup

The choice of welding setup depends on the necessary or desired weld quality, on the welding equipment available, on the original cost of welding equipment and its economical application, on the electrical power available to supply the welder, on the design and shape of the parts to be welded and on the consistency of the parts themselves resulting from previous forming operations.

The best weld quality results from welding setups making Class A welds. The average shear strength is highest, the percentage spread is least, the metallurgical structure is soundest and the energy required is least in comparison to the other classes of welds. It is good judgment to use Class A welds if possible.

Class A Weld



Nugget diameter, 0.340 in.; penetration, 75%

Class B Weld

Nugget diameter, 0.324 in.; penetration, 73%

Class C Weld

Nugget diameter, 0.316 in.; penetration, 70%

Fig. 11—Photomacrographs of Welds in 0.090-In. Thickness

Table 2

LOW CARBON STEEL SPOT WELDING DATA CHART- SINGLE IMPULSE WELDING

DATA COMMON TO ALL CLASSES OF SPOT WELDS						WELDING SET-UP FOR BEST QUALITY - CLASS A WELDS					WELDING SET-UP FOR MEDIUM QUALITY - CLASS B WELDS					WELDING SET-UP FOR GOOD QUALITY - CLASS C WELDS				
THICKNESS OF EACH OF THE TWO WORK PIECES		ELECTRODE DIA. & SHAPE D, d, 120°		MINIMUM WELD SPACING ℄ TO ℄ (NOTE 4)	MINIMUM CONTACTING OVERLAP L (NOTE 5)	WELD TIME (NOTE 6)	ELECTRODE FORCE	WELDING CURRENT	NUGGET DIA.	AVERAGE TENSILE SHEAR STRENGTH ±14%	WELD TIME (NOTE 6)	ELECTRODE FORCE	WELDING CURRENT	NUGGET DIA.	AVERAGE TENSILE SHEAR STRENGTH ±17%	WELD TIME (NOTE 6)	ELECTRODE FORCE	WELDING CURRENT	NUGGET DIA.	AVERAGE TENSILE SHEAR STRENGTH ±20%
INCHES	USS GAGE	MIN D INCHES	MAX d INCHES	INCHES	INCHES	CYCLES	POUNDS	AMPS	INCHES	POUNDS	CYCLES	POUNDS	AMPS	INCHES	POUNDS	CYCLES	POUNDS	AMPS	INCHES	POUNDS
.010	32	3/8	1/8	1/4	3/8	4	200	4000	.13	235	5	130	3700	.12	200	15	65	3000	.11	160
.021	25	3/8	3/16	3/8	7/16	6	300	6100	.17	530	10	200	5100	.16	460	22	100	3800	.14	390
.031	22	3/8	3/16	1/2	7/16	8	400	8000	.21	980	15	275	6300	.20	850	29	135	4700	.18	790
.040	20	1/2	1/4	3/4	1/2	10	500	9200	.23	1350	21	360	7500	.22	1230	38	180	5600	.21	1180
.050	18	1/2	1/4	7/8	9/16	12	650	10300	.25	1820	24	410	8000	.23	1700	42	205	6100	.22	1600
.062	16	1/2	1/4	1 1/16	5/8	14	800	11600	.27	2350	29	500	9000	.26	2150	48	250	6800	.25	2050
.078	14	5/8	5/16	1 3/8	11/16	21	1100	13300	.31	3225	36	650	10400	.30	3025	58	325	7900	.28	2900
.094	13	5/8	5/16	1 5/8	3/4	25	1300	14700	.34	4100	44	790	11400	.33	3900	66	390	8800	.31	3750
.109	12	5/8	3/8	1 13/16	13/16	29	1600	16100	.37	5300	50	960	12200	.36	5050	72	480	9500	.35	4850
.125	11	5/8	3/8	2	7/8	30	1800	17500	.40	6900	60	1140	12900	.39	6500	78	570	10000	.37	6150

Low carbon steel has a very wide "plastic range". This means there are many set-ups with various combinations of Weld Time, Electrode Force, and Welding Current which can be used to produce good welds. The Welding Data Chart indicates three (3) set-ups which list Class A, or best welds, involving short Weld Time, high Electrode Force and high Welding Current; Class B, or medium welds, with medium Weld Time, medium Electrode Force and medium Welding Current, as well as Class C, or good welds, with long Weld Time, low Electrode Force and low Welding Current. All three set-ups will produce good welds with uniform nugget size and penetration.

Consideration should be given to the fact that production parts seldom fit perfectly and some reserve of Electrode Force over that required to make welds with the lowest forces should be provided. Steels of higher temper also require higher Electrode Forces.

The Welding Data Chart indicates that the Average Tensile Shear Strength, the Consistency of Strength values (as indicated by the plus and minus tolerances on the average strength) and the nugget diameters change slightly with Class A welds having the highest values and Class C welds having the lowest values.

Hundreds of tested welds also indicate that:

(a) Welds fail in tensile-shear test by pulling "buttons" from one of the work pieces in the majority of welds of all three classes.

(b) There is a slight change in internal porosity as the welding force decreases with Class C welds having slightly more porosity than Class A and B welds.

(c) Penetration of the nugget into each of the two welded work pieces, surface indentation, sheet separation, remains essentially constant for all three classes.

(d) Class C welds have greater work heating and surface discoloration than Class A welds.

NOTES:

1 Low carbon steel is hot rolled, pickled, and lightly oiled with an ultimate strength of 42,000 to 45,000 PSI similar to SAE 1005 - SAE 1010.

2 Electrode material is RWMA Class 2 alloy.

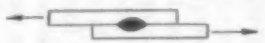
3 Surface of steel is lightly oiled but free from grease, scale or dirt.

4 Minimum weld spacing is that distance for which no increase in welding current is necessary to compensate for the shunted current effect of adjacent welds.

5

6 Weld time is indicated in cycles of 60 cycle frequency.

7 Tensile shear strength values are based on recommended test sample sizes.



THICKNESS	WIDTH	LENGTH
.000" to .029"	5/8"	3"
.030" to .058"	1"	4"
.059" to .115"	1 1/2"	5"
.116" to .190"	2"	6"

8 Tolerance for machining of electrode diameter "d" is ± .015" of specified dimension.

9 Electrode force does not provide for force to press ill-fitting parts together.

Table 3—Comparison of Calculated and Measured Values of Welding Resistance and Factors Affecting Welding Resistance

Thickness of Each Piece, In.	Welding Current, Amp.	Electrode Force, Lb.	Force Density, Lb./Sq. In.	Current Density, Kiloamp./Sq. In.	Welding Resistance, R_W (Microhms)	
					Measured	Calculated
0.032	8,000	425	15,400	291	125	128
0.032	6,400	280	10,300	233	150	146
0.032	4,730	135	4,900	172	190	189
0.060	11,500	800	16,300	234	102	97
0.060	9,000	490	10,000	183	115	116
0.060	6,850	245	5,000	139	140	158
0.090	14,300	1250	16,300	187	78	78
0.090	11,400	770	10,000	149	102	98
0.090	8,520	380	5,000	112	132	137
0.120	17,120	1800	16,300	155	69	66
0.120	12,800	1110	10,000	116	90	82
0.120	10,000	550	5,000	91	126	122

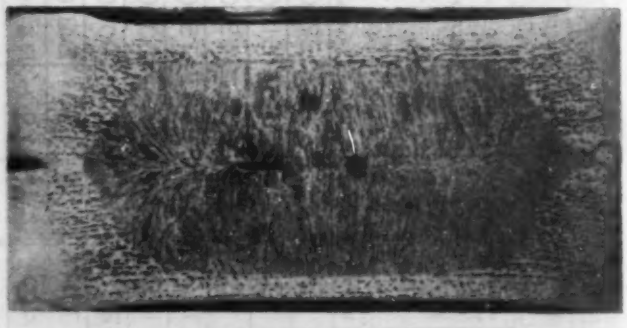
A fabricator possessing welding equipment may find it impossible to make Class A welds as the maximum electrode force available may be insufficient to supply the recommended value. In such cases welding setups for Class B welds can be selected and very good welds may be made although the actual weld period in the machine will be increased. Spot welders are manufactured in a range of sizes depending on the maximum electrode force capacity and kilovolt-ampere rating. The original cost is partially related to the electrode force capacity available as larger forces require heavier mechanical construction to reduce deflection of the component parts and insure adequate welder life. For a specific production application it might be considered too costly to purchase spot welding equipment for Class A welds but the comparatively less expensive equipment needed for Class B welds would be economically justified. This change in selection of class of weld results in a reduction in size of the spot welder as the required electrode force capacity is reduced approximately 35%. Should several production applications be under consideration, a possible decision would involve selecting welding equipment to make Class A welds in the major applications and Class B welds or Class C welds in the minor ones. The latitude offered in welding setups from Class A through Class C welds is a challenge to the production engineer to properly select and apply his equipment.

The capacity of an installed power system in a plant and the feeding system from the power company must always be investigated as to its ability to supply the electrical power demand necessary for spot welding. Welding setups for Class B welds require approximately 77% of the current for Class A welds while those for Class C welds require 59% of the current for Class A welds. As the power demand or kilovolt-ampere varies approximately as the square of the current, the kilovolt-ampere demands are 60% for Class B and 36% for Class C in comparison to Class A. Generally, such reductions will cause less disturbance on the power supply lines and require less kilovolt-ampere rating capacity of the welder power plant. Longer weld timing intervals associated with smaller welding currents require less precise and less expensive welder controls and thus further diminish the original cost.

The design and shape of some parts to be spot welded require offset electrodes where the mechanical strength is insufficient to support the electrode forces required for Class A welds. Providing the electrodes can be properly water cooled, the problem is readily solved by selecting setups for Class B or Class C welds requiring less electrode force.

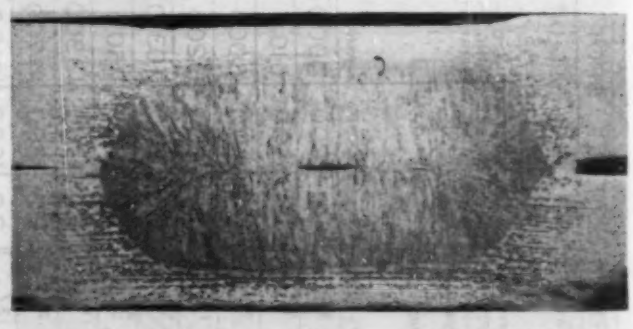
Low electrode force values such as used in making Class C welds make it mandatory to have properly formed and aligned parts at the joint to be welded. It is inadvisable to use Class C welds on any parts in which the forming and shaping may be inconsistent enough to re-

Class A Weld



Nugget diameter, 0.395 in.; penetration, 73%

Class B Weld



Nugget diameter, 0.386 in.; penetration, 70%

Class C Weld

Nugget diameter, 0.372 in.; penetration, 65%

Fig. 12—Photomacrographs of Welds in 0.120-In. Thickness

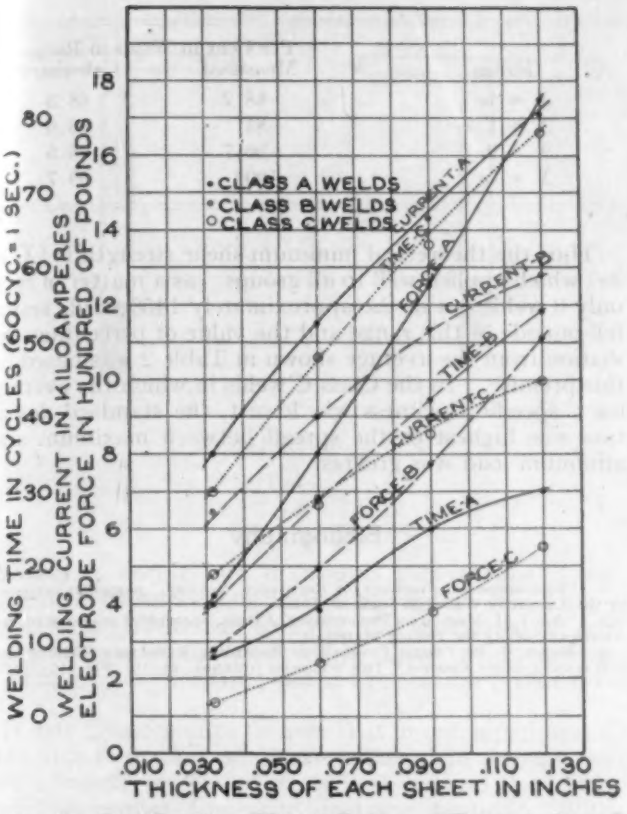


Fig. 13—The Variation of Welding Current, Electrode Force, and Weld Time with Stock Thickness for Class A, Class B and Class C Welds

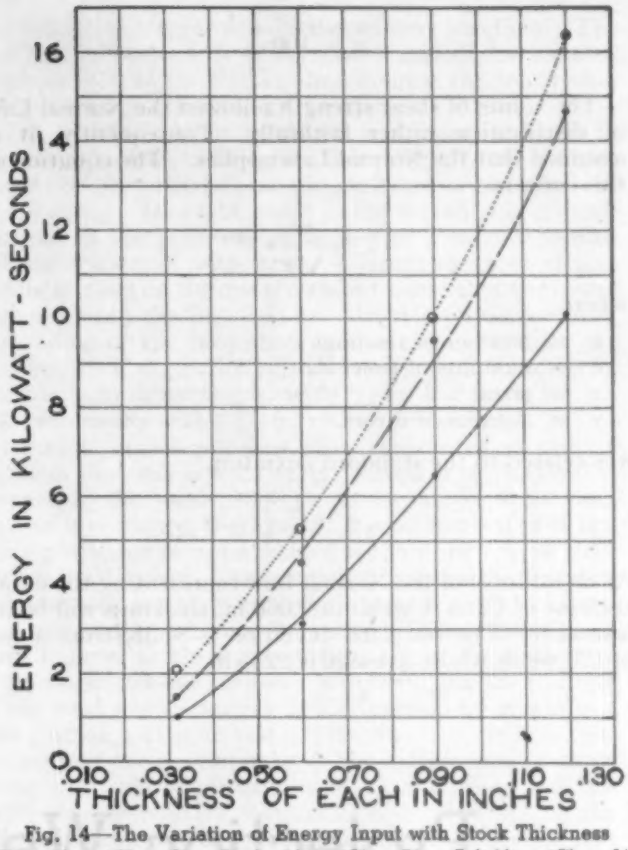


Fig. 14—The Variation of Energy Input with Stock Thickness
Dotted line (Class C). Dashed line (Class B). Solid line (Class A).

quire a portion of the electrode force to be expended in making the parts contact at the joint. In assemblies requiring a number of spot welds in a small area the extra heat dissipation around the Class C weld could cause undesirable distortion and discoloration.

Welding setups for Class C welds require more precise production control methods both in the parts themselves and in the welding process. Should any factor such as poor surface condition, ill fit of parts, misalignment of electrodes, poor voltage regulation, etc., cause the expulsion of metal during welding, the shear strength will be markably reduced from the anticipated average strength. Class C welds should not be employed if any of the above conditions are present unless the necessary average weld shear strength is less than the average weld shear strength shown in Table 2.

The minimum weld spacing (between weld centers) requiring no change of current in the welding setup to obtain welds of equal nugget diameters was found to be independent of the welding setup.

Suggestions for Application of Class A, Class B and Class C Welds

The variation of welding setup and the resulting weld qualities have been presented from the viewpoint of the welding engineer who must make a weld desired by the product engineer. The product engineer specifies the requirements of the weld, oblivious of weld classification, and the welding engineer selects the welding setup to give the desired weld properties with the welding equipment available or attainable.

The ability of any standard design of spot welder of a specific size to weld certain thicknesses of steel is often included in the technical literature of resistance welder manufacturers. This ability, if judged from the literature, may be confusing and even contradictory between various manufacturers for the same type and size of spot welder. This condition arises because no distinction is made between classes of welds. Some manufacturers rate in Class A and possibly Class B welds while others include welds of less quality than Class C welds without explaining these variations of weld quality. As welding machines may be rated in terms of weld quality and such weld quality can be readily calculated from the welding variables, it is suggested that consideration be given to rotating machines in terms of ability to make Class A, Class B and Class C welds at a certain rate per minute.

APPENDIX A

Significance of Average Value $\bar{X}$, Standard Deviation, σ, and Coefficient of Variation, v

The A.S.T.M. method of presentation of data may not be familiar to the reader so a brief explanation is included in this appendix.

The average, $\bar{X}$, of a set of n numbers $x_1, x_2, x_3 \ldots x_n$ is

$$\bar{X} = \frac{x_1 + x_2 + x_3 \ldots x_n}{n}$$

where n = number of readings.

The standard deviation, σ, of a set of numbers is the square root of the average of the squares of the deviations of the numbers from their average $\bar{X}$.

$$\sigma = \sqrt{\frac{(x_1 - \bar{X})^2 + (x_2 - \bar{X})^2 + \ldots (x_n - \bar{X})^2}{n}}$$

The coefficient of variation, v, of a set of n numbers is the ratio of their standard deviation to their average expressed as a percentage.

$$\sigma = 100 \frac{\sigma}{\bar{X}}$$

The values of shear strength followed the Normal Law of distribution rather faithfully. Consequently, it is assumed that the Normal Law applies. The equation of this curve is

$$Y_x = \frac{nh}{\sqrt{\pi}} e^{-h^2x^2}$$

where

n = number of readings
h = modulus of precision
x = error
y = number of errors.

h is related to the standard deviation

$$\sigma = \frac{1}{2} \cdot \frac{1}{h}$$

As an example of the Normal Law representing the data, the case of Class A welds in 0.060 in. thickness will be illustrated. The standard deviation is 81 lb. from a set of 120 welds whose average is 2235 lb.

Range	Per Cent in Welds in Range Measured	Calculated
$\bar{X} \pm 1\sigma$	68.2	68.3
$\bar{X} \pm 1.5\sigma$	84	86.6
$\bar{X} \pm 2\sigma$	96.7	95.5
$\bar{X} \pm 3\sigma$	100	99.7

Thus the theoretical minimum shear strength is $(\bar{X} - 3\sigma)$ which applied well to all groups: as a matter of fact, only 3 welds out of the approximately 1450 welds tested fell outside of this range and the value of percentage deviation from the average shown in Table 2 was based on this premise. In the Class C welds in which the average for a specific thickness was lowest, the standard deviation was highest or the spread between maximum and minimum load was greatest.

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Projection Welding Push Rod

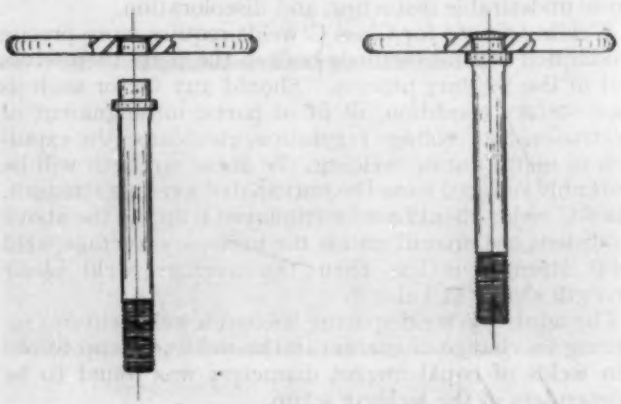
By E. B. Rhodes*

OUR push-rod assembly was formerly made up of $^5/_8$-in. rod, riveted onto a 4-in. diaphragm plate (see Fig. 1). It was necessary in this construction to provide a shoulder on the rod to support the riveted end, consequently, it had to be designed from a forging in order to economize on material and labor which would have been necessary had the part been machined from bar stock. This design necessitated a large stock of forgings in our stockroom to accommodate the numerous different lengths of push rods required to meet the demands of the many different models required to adapt air brakes to all types of commercial vehicles.

The plate was a steel stamping made from S.A.E. 1020 steel, $^5/_{16}$ in. thick and approximately 4 in. in diameter. The rod was made from S.A.E. 4140 bar stock $^5/_8$ in. in diameter and heat treated to 32–34 Rockwell "C" scale.

The completed push-rod and push-plate assembly is used in all air brake chambers made by our company. This Company's product is used throughout the world to stop all types of heavy-duty trucks and buses. All parts that go into the making of a set of air brakes must be of the best quality and construction in order to insure the greatest amount of safety that it is possible to obtain. The push-rod and push-plate assembly that we are discussing is a critical part of the air brake function, so it must be absolutely fool-proof from a failure standpoint. In addition to this, this particular assembly is one of the most highly stressed units in the entire air brake system.

Our first problem was the difference in analysis between the bar stock and the plate. This did not present too much of a problem from a strictly welding angle. However, reasoning indicated that at the welded section of the rod a brittleness would develop. This is exactly what happened and this represents the principle problem involved.

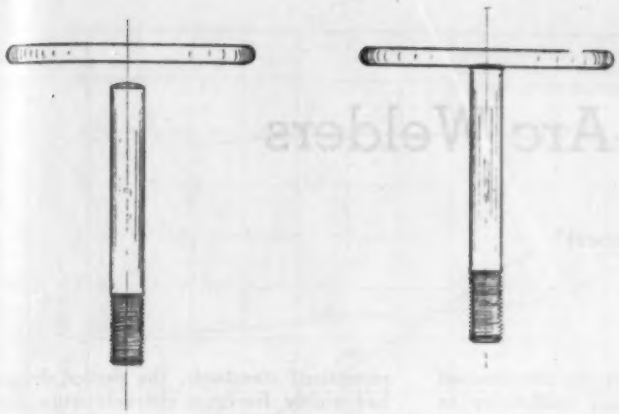


Riveted Construction

Fig. 1

The elimination of this embrittlement could have been accomplished through a drawing operation following welding. This would have added an operation and a proportionate increase in cost. To avoid this, we carried on very extensive experimental work particularly with electrical control devices in an attempt to weld and anneal in the same machine setting. Early in our experimental work we were able to accomplish this purpose.

* Tool and Methods Engineer, Bendix-Westinghouse Automotive Air Brake Co., Elyria, Ohio.



Welded Construction

Fig. 2

The way it worked out, it entailed a dwell time in the machine between welding and annealing that would have reduced our production to 25%. So we carried on our experiments in an effort to combine these two operations in a single machine setting and at a reasonable production rate.

It may be interesting to note that in our experimental work, due to market conditions rather than through our own intentions we welded steels, both rod and plate, that varied somewhat from our steel specifications. With some such combinations of steels we were enabled to arrive at our ultimate goal at once. However, such controls proved worthless when the proper analysis steels were welded.

After innumerable trials and tests we finally arrived at proper controls and satisfactory machine settings to produce a good weld and a fast annealing cycle in the same machine setting. In other words, we produced a good weld between the S.A.E. 4140 bar stock and the S.A.E. 1020 steel plate. The post heat or annealing cycle relieved embrittlement strains encountered during the welding process and produced the required hardness of 32–34 Rockwell "C" scale.

Without question, the most outstanding development on the machine is the post-heat annealing arrangement. It is composed primarily of a Westinghouse synchronous spot-welding control panel with phase shift heat control incorporated along with a control panel. An electronic temporary unit together with an electronic N.E.M.A., size 9B weld timer is hooked in series with an electronic N.E.M.A., size 8B weld timer. The welding dies are made from a copper alloy and are water-jacketed for cooling purposes.

In operation the push plate is positioned in a die located in the machine and is held in place by a three-jaw fixture. The push rod is then held in an air-operated set of jaws, the bottom of the rod being laid against an anvil to absorb the shock of the pressure exerted by the cylinder behind the upper ram in the welding machine. The machine is operated by a foot control and all the operator must do is load the fixture then depress the foot pedal. The rest of the operation is automatic.

The newly designed push-rod and plate is shown in Fig. 2. The hole in the plate has naturally been eliminated and the push rod is now made from bar stock instead of a forging. It can be noted in the sketch (Fig. 2) that the end of the push rod is formed to a natural radius. We experimented with many different types of shapes before settling on the one shown but found that the round end produced the best results. In this particular case, the radius of the projection was found to produce the best results if the radius was the same as the diameter of the bar. In other words, with $^5/_8$-in. bar stock we got our best results with a $^5/_8$-in. radius projection.

Another major problem that confronted us and a problem that still is not entirely solved is our method of inspecting the welds 100%. As far as we have been able to investigate, there is not a good method of determining whether or not a welded section, such as we have here, is good or bad. As I explained previously the push-rod assembly is a very critical part of the air brake function and every part must be perfect. There must be no weld failures or the consequences might be disastrous.

Of course, the one sure way of determining the strength of the weld was to destroy welded section by means of a pull test or a fatigue test. This was the method used throughout the development of the machine and method along with microphotographs of cross sections. Naturally, this destructive method of test could not be employed for long and our problem was to make certain that every weld was perfect and that there would be no danger of a weld failure.

As it stands now we are holding the push-rod assembly in a horizontal position, clamping the push plate in a solid fixture and, by means of an air cylinder, we are applying a load of 1300 lb. against the side of the push rod at a distance of 2 in. from the push plate. We then measure the deflection in the thousandths of an inch at a given distance from the plate.

If the assembly will stand this test and the deflection measured is within a given specification, we are reasonably sure we have a weld and a condition of metal that is within the range of the most severe operation to which the push-rod assembly might be subjected.

The noisy riveting machine complaint is now eliminated and we have in place of it a somewhat silent welding machine. In addition to this, the new method of welding will save our company approximately $40,000 annually in material and labor. Our largest savings are accounted for by the substitution of bar stock in place of forgings. This represents a substantial savings in material costs. A major contribution in labor saving is the fact that the forging was machined on lathes and the bar stock is an automatic machine operation. In addition to this we found that the welding operation is by far faster than the riveting operation and therefore we have a further substantial saving in assembly cost.

Limited-Input Arc Welders

By E. Steinert*

THE important role played by arc welding during the last war, and the widespread publicity given the art, popularized welding to the extent that a large new potential market was developed.

The demand of this market is for one or more moderately small ratings of arc welders suitable for the average welding job on the farm, repair shop, garage and home workshop. The transformer type arc welder appears to be best suited for the requirement of this market, because of simplicity and low cost.

The development, during recent years, of highly stabilized electrode has permitted the design of transformer type welders with open-circuit (striking) voltage on the order of 50 v. This reduction in voltage from the industrial standard of 80 v. has resulted in a corresponding decrease in size of the welder, and a proportional reduction in the amount of kva. drawn from the power supply line. A further reduction in kva requirements is made possible by the use of built-in capacitors for power factor correction. The combination of these two design factors, reduced open-circuit voltage and power factor correction, has enabled the welder designer to offer a higher maximum welding current output for a given limited kva input.

Although this type of welder is limited to use with low-voltage stabilized electrode, its usefulness is not thereby restricted for the type of service for which it is intended. In addition to the highly stabilized electrode for welding ordinary mild steel, other electrodes with similar characteristics have been developed, and are available, for welding many steel alloys and for hard surfacing.

The versatility of this type of welder has been further increased by the introduction of the carbon arc torch employing cored carbons stabilized for low-voltage alternating current. The use of such a torch rounds out the application of this class of welder to include welding of aluminum, copper, brasses, bronzes, etc., in addition to providing a tool for brazing, soldering and supplying heat for light forging, preheating and tempering operations.

It should not be inferred that the Limited-Input transformer type welder is an entirely new and recent development, because actually welders of this general class, designed for light duty have been manufactured for several years. However, a real advancement was made during recent months in the further development of this class of welder by the introduction of standards to promote uniformity in ratings and characteristics.

Owing largely to the nonexistence of recognized standards, the earlier designs had widely divergent characteristics, particularly with reference to welding performance, load ratings, open circuit volt-

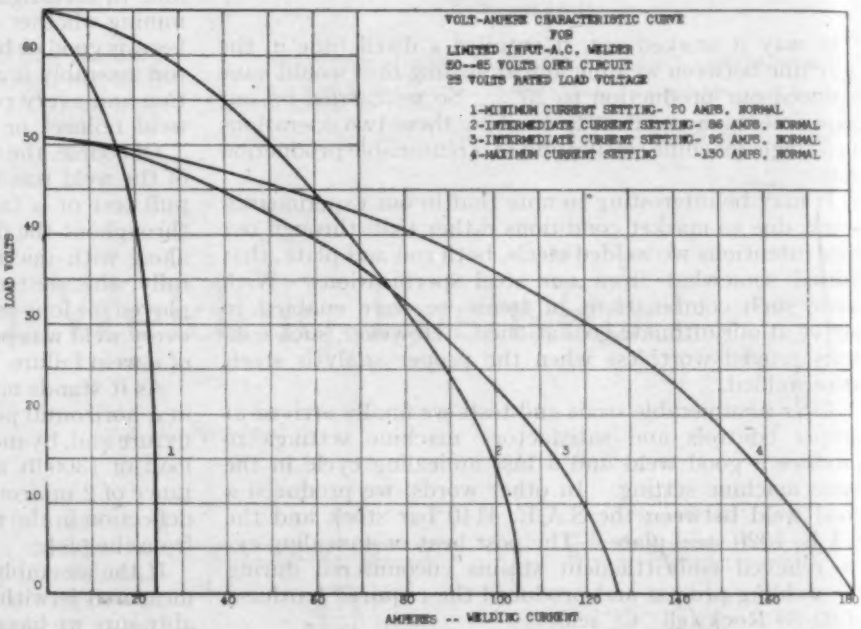


Fig. 1—Static Volt-Ampere Characteristic Curves. Secondary Current vs. Load Volts

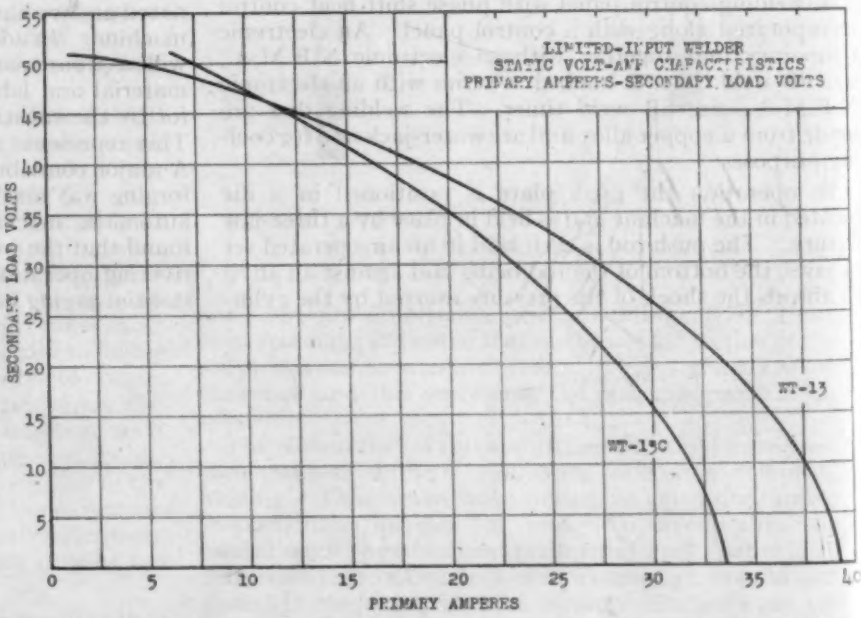


Fig. 2—Static Volt-Ampere Characteristic Curves. Primary Current vs. Load Volts

* Engineering Manager, Welding Apparatus Section, Welding Dept., Westinghouse Electric Corp., Buffalo, N. Y.

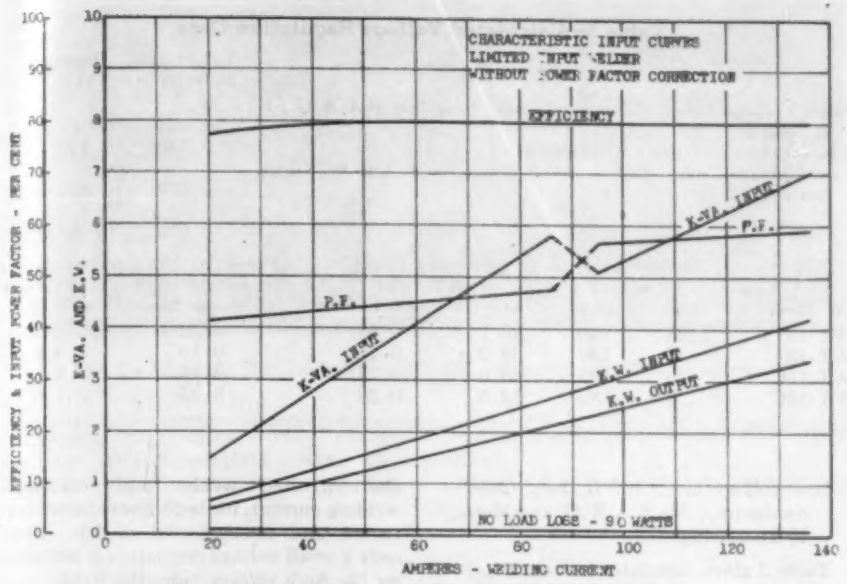


Fig. 3—Electrical Performance Curves, Type WT-13

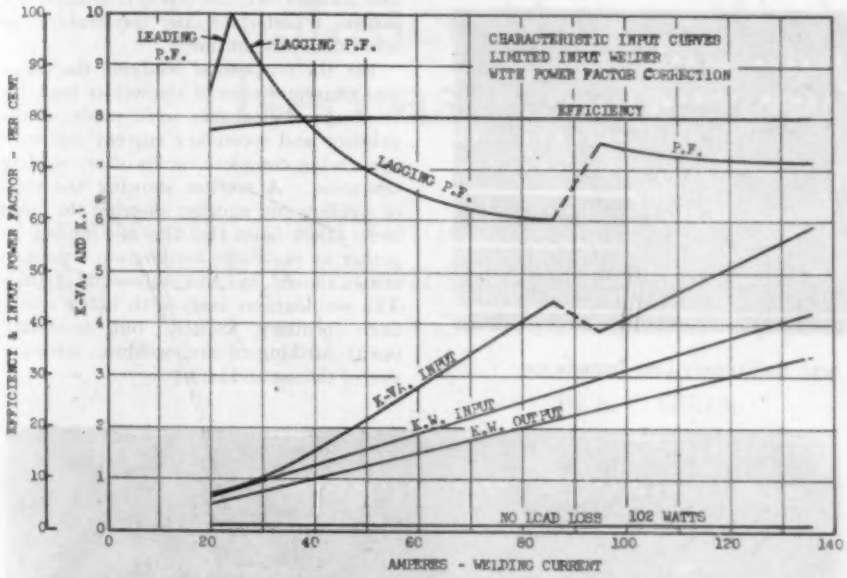


Fig. 4—Electrical Performance Curves, Type WT-13C (Power Factor Corrected)

age and power requirements. Lack of uniformity, for example, in specifying electrical characteristics on the nameplates added to the confusion of persons applying and servicing these welders. Because of the widely different characteristics and lack of, or misinterpretation of, data, many of these welders were connected to power lines of unsuitable capacity, resulting, oftentimes, in dissatisfaction to the operator and power company.

Individual efforts on the part of several utilities, rural co-ops and the R.E.A., to regulate and limit the application of arc welders on their power lines, brought the attention of N.E.M.A. to the need for a uniform standard covering this new class of welders. As a result, a new standard was introduced for arc welders below 200-amp. rating and designated "Limited-Input Type Transformer Arc Welders."

This new standard was developed to cover in particular welders served by single-phase power lines of limited capacity supplying rural consumer or small community. The standard was designed to promote manufacture of welders with maximum welding serviceability based on practical consideration of welding current range, duty cycle and limited kva. input.

Because these welders are usually connected to power supply lines of limited capacity, particularly in rural areas, the welder may represent a considerable overload on the power circuit to which it is connected. In view of this, it is of considerable importance to the power company to know the characteristics of the apparatus, in so far as they affect the thermal capacity and voltage regulation of the power supply circuit.

Data from calculation and tests, included as a part of this paper, were made on two typical Limited-Input welders rated 20–130 amp., 25 v. (load), 230 v., 60 cycles primary. One of the units was equipped with a capacitor for primary power factor correction and the other was noncorrected. In the accompanying data, these units are identified as WT-13 for the noncorrected and WT-13C for the power factor corrected unit.

The static volt-ampere characteristic curves are shown in Fig. 1. These curves show the steady state relation between secondary current and resistance load voltage, with normal primary voltage applied. As indicated by the curves, this design has an open-circuit secondary voltage of 50 v. on the high end of the welding current range, and 65 v. on the low end. This arrangement reduces the maximum primary input kva. and improves arc stability at the lower current settings where the arc is inherently less stable.

The static volt-ampere characteristic curves in Fig. 2 show the relation between primary current and resistance load voltage on the secondary. The curves shown are for the maximum welding current setting. The current value at the left end of the curves represents the no-load input current with secondary open-circuited.

In both Figs. 1 and 2, the maximum current values at 0 v. were measured with the secondary terminals of the welder short circuited. These short-circuit current values represent an extreme condition, which is only approached in actual operation because of impedance in welding leads, electrode and work during momentary shorting of the electrode.

Figures 3 and 4 show the characteristic electrical input and performance curves for welder models WT-13 and WT-13C, with and without power factor correction, respectively. The curve data are based on the rated resistance load of 25 v., which is equivalent to operating conditions under welding arc load.

It is now general practice in most rural areas to permit connection of Limited-Input welders, with rated primary current not exceeding 37.5 amp., on

Table 1—Approximate Tripping Time in Minutes for Breaker in 3-Kva 7200/240-V., Single-Phase Self-Protected Transformer

Welder	Welder Only, Transformer Starting at Ambient	Welder Only, Following Full Load on Transformer	Welder in Addition to Full Load on Transformer, Following Full Load on Transformer*
WT-13 Short-circuit	45	30	8
WT-13 25 v.	105	60	20
WT-13C short-circuit	75	45	15
WT-13C 25 v.	240	150	30

* Assumes welder load and other load in phase.

single consumer outlets supplied by 3-kva. step-down transformers. The following data are intended to show the effect of the welder load on a typical rural line.

Table 1 is a tabulation of approximate time data, giving the time in minutes required to trip the breaker in a 3-kva. self-protected transformer under different welder load conditions. Since the thermal characteristics of the breaker are closely coordinated with the heating of the transformer windings, the breaker tripping time represents a safe time of loading.

These data are based on maximum welding current setting and on extreme conditions of loading, greater than likely to occur in operation. The short-circuit load condition is with welder terminals short circuited. Actual current during striking or momentary shorting of arc is considerably less, and may exist for only a second or two. The time data are based on continuous loading—that is, without interruption of the welding current—whereas the welder is rated at 20% duty cycle, or 2 min. operation in 10 min.

Table 2—Calculated Voltage Regulation Data

	Resistance (Referred to 240-v. Side)	Reactance (Referred to 240-v. Side)
High-Voltage Line: 7200 v., 10 miles long, No. 6 A.W.G., 4-ft. spacing	0.046	0.017
Transformer: 3 kva., 7200/240 v.	0.550	0.342
Low-Voltage Line: 240 v., 100 ft. long, No. 6 A.W.G., 10-in. spacing	0.079	0.023
	0.675	0.382 Ohm

Welder	Welder Load (Secondary) Volts	Amp.	Primary Input to Welder Amp.	Power Factor	Per Cent Voltage Regulation At End of High-Voltage Line	At Primary of Welder
WT-13	25	130	30.7	0.58	0.52	9.1
WT-13	0	180	39.2	0.17	0.40	8.5
WT-13C	25	130	26.0	0.72	0.49	8.1
WT-13C	0	180	33.5	0.20	0.35	7.0

Low-voltage line: 100 ft. long (200-ft. conductor), No. 6 A.W.G. conductor, 10-in. spacing.

Table 2 gives calculated voltage regulation at the end of the high-voltage line and at the welder, under conditions of short-circuited welder and maximum welding current, for both power factor corrected and noncorrected models. Since only a small voltage regulation is produced on the high-voltage side, the welder load should cause no objectionable interference to adjacent consumers. Where more than one consumer is supplied from one transformer, the obvious solution is a larger transformer or, preferably, an additional transformer.

For the purpose of studying the transient characteristics of the welder load, 10-ft. long oscillograms were made of the primary and secondary current and voltage during complete cycles of arc-welding operation. A section showing the start of welding and another showing the finish were taken from the film and joined together to make the oscillogram reproductions shown in the following figures. The oscillograms start with idling condition (primary excited, but secondary open), striking of arc, welding, interruption of the arc and idling.

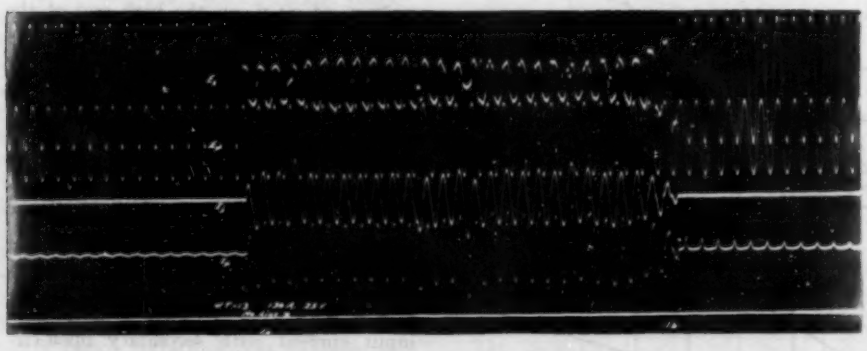


Fig. 5—Welding Oscillogram for WT-13, with No Primary Line Impedance

From these data it is obvious that normal operation of the welder is unlikely to cause breaker tripping, even though the transformer has been and is continuing to carry rated load, in addition to the welder.

For the purpose of evaluating the amount of voltage regulation caused by the welder on a rural circuit, the following conditions were assumed:

High-voltage line: 10 miles long (20 miles conductor), No. 6 A.W.G. conductor, 4-ft. spacing.

Transformer: 7200/240 v., 3 kva., single phase.

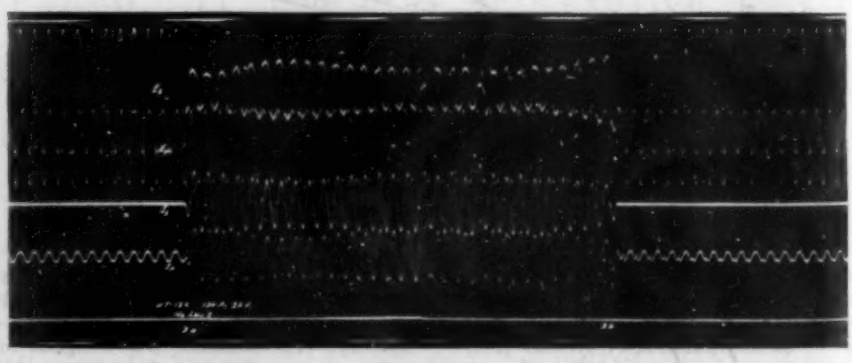


Fig. 7—Welding Oscillogram for WT-13C with No Primary Line Impedance

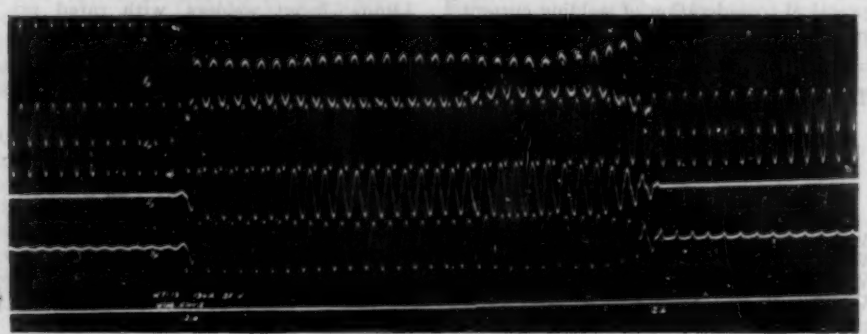


Fig. 6—Welding Oscillogram for WT-13 with Primary Line Impedance

Figure 5 shows the arc-welding cycle performed on the WT-13 set at maximum welding current. Figure 6 was made under the same conditions as Fig. 5, except that resistance and reactance of values corresponding to those given above were connected in series with the primary line to simulate the effect of transformer and line impedances.

Figures 7 and 8 were performed on the WT-13C, but correspond otherwise to Figs. 5 and 6, respectively.

A study of these oscillograms bears out the following points:

1. The absence of violent surges, or

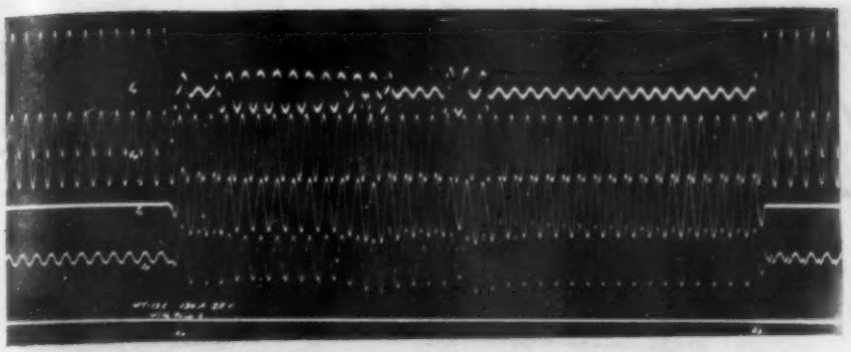


Fig. 8—Welding Oscillogram for WT-13C, with Primary Line Impedance

fluctuations, in primary current during any part of the operating cycle. The fluctuations are practically within the limits predicted from the static characteristics.

2. Under condition of momentarily shorted electrode, the secondary voltage is approximately 4.5 v. The rise in primary current, as a result of the momentary short, is approximately 20% over that for normal arc condition on both the power factor corrected and noncorrected welders.

3. The effect of primary line impedance of values given above for combined high-voltage line, transformer and low-voltage line is to reduce the primary voltage at the welder 8% on the power factor corrected welder, and 10% on the noncorrected welder, when operating at rated maximum load.

4. The secondary voltage does not exceed the normal open-circuit voltage during any part of the operating cycle. The operator, therefore, is not exposed to any voltage in excess of the normal open circuit value, which is limited to 65 v.

Resistance-Seam-Welded Sacks Used as Hydraulic Presses*

For Exerting Extreme Forces in Confined Spaces of Various Basic Configurations. Initially Devised for Testing Welds of Dissimilar Metals

By R. T. Gillette†

IN RESISTANCE seam welding, a typical example of which is shown in Fig. 1, a large portion of the applications are required to be pressure tight in a range from the lowest pressures obtainable to those of several thousand pounds per square inch. The demand that modern industry has placed on the use of various metals and combinations of dissimilar metals in these applications requires a simple testing method for determining their weldability.

Pillow Method of Testing Welded Seams

To meet this demand the pillow or sack method of

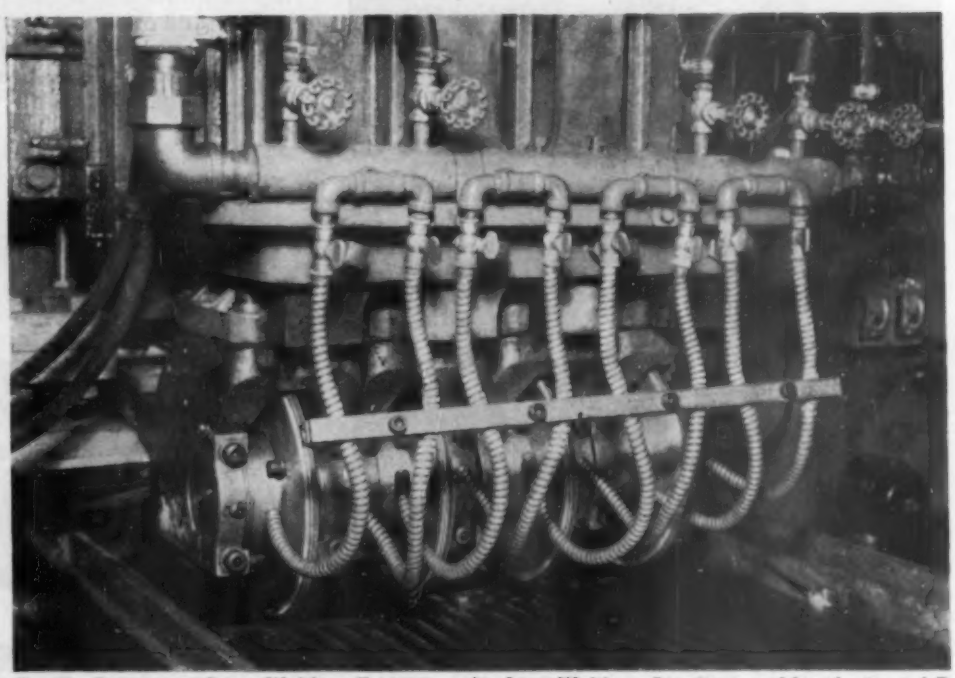


Fig. 1—Resistance Seam Welding Equipment for Line Welding Operation in Manufacture of Refrigerator Condensers

* Reprinted from *General Electric Review*, July 1946.

† Schenectady Works Lab., General Electric Co.

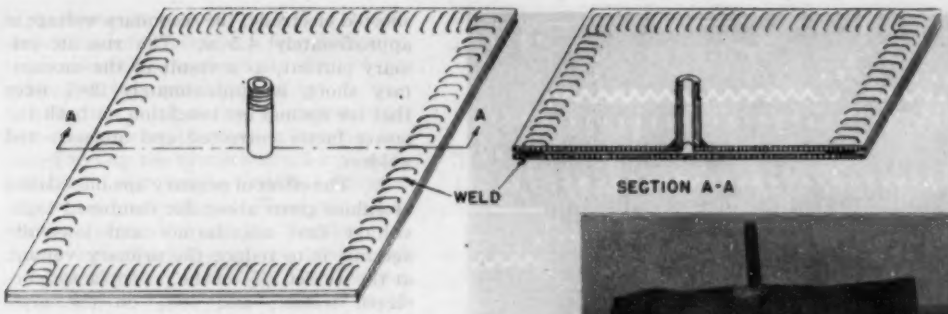
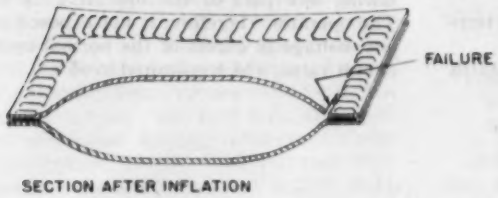


Fig. 2—Construction of a Test Pillow for Hydraulic Tests of Welded Seams; Such Construction, Modified According to Geometrical Requirements, Is Used Also in Pillows for Applying Large Hydraulic Forces Externally



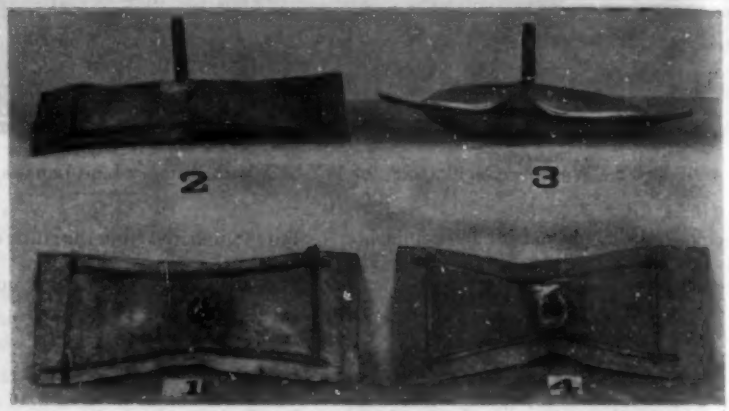


Fig. 4—Four Samples of Pillows Used for Testing Welds; Failure Occurred at Pressures Ranging from 1600 to 2000 Psi.

testing was developed, in which the weld is tested by hydraulic pressure. This is accomplished by taking two pieces of the test material having the desired shape, thickness and size, drilling a small hole through one of them and welding or brazing a small pipe nipple over the hole. The two pieces are then seam welded around the outer edges as shown in Fig. 2. Hydraulic pressure is then applied through the nipple, usually with a small manually operated hydraulic pump, such as the one illustrated in Fig. 3.

For a pump of this type, pressure readings are taken on the 400-lb. gage when thin materials are being tested to insure an accurate reading; for heavier materials the 5000-lb. gage is used. The gage not in use may be shut off by its respective valve, or gages of other pressure values may be substituted. The load on the pillow is calculated in pounds per square inch for the area of the pillow inside the weld line.

The failure should occur in the sheet inside the weld line, as shown in Figs. 2 and 4, which latter pictures a typical group of test pieces. If the failure occurs by parting of the sheets through the weld, the weld is considered unsatisfactory.

Application as Hydraulic Presses

The magnitude of the forces exerted in the use of this method of pressure testing seam welds suggested also the utilization of the metal pillows or sacks for hydraulic presses or pressure devices in which high pressure with small over-all travel is required. Such utility is found particularly in applications where standard hydraulic presses are not suitable or convenient.

Used successfully to replace shafting presses for pressing shafts in various types of machinery, this method has been applied also to the removal of gears, brake drums, pulleys and other machine parts which have been shrunk or stuck on shafts or other parts. It may be used also in the stretching of large-size rings as well as the straightening of heavy members.

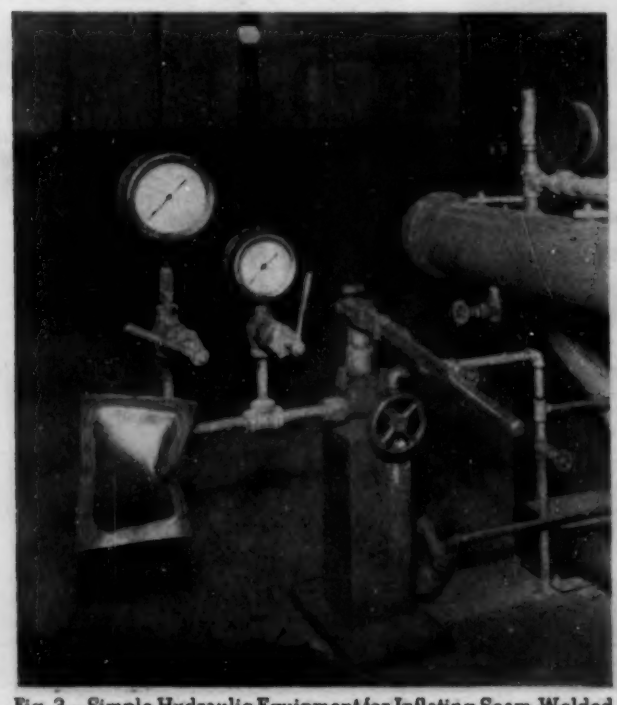


Fig. 3—Simple Hydraulic Equipment for Inflating Seam-Welded Pillows for Test or for Pressing Operations

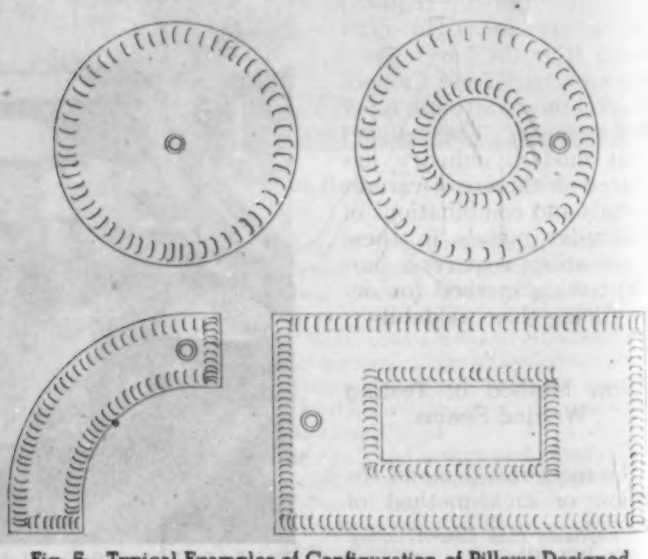


Fig. 5—Typical Examples of Configuration of Pillows Designed for Use in Hydraulic Pressing Operations

The use of these sacks should find a wide field of applications as they may be made in a large range of shapes or sizes to fit the geometric contour of a given job. For instance, as a dimensional example, they may be made 2 in. wide and 4 ft. long; their shapes may be square, horseshoe, circular, or segments of a circle, as shown in Fig. 5. These shapes and sizes are readily suggested by the work to be performed. As an example, if a collar, pulley or brake drum has to be removed from a shaft, it would not be possible to use a complete ring sack. The pillow would be made in two or more segments, and when assembled, might have the shape of a horseshoe.

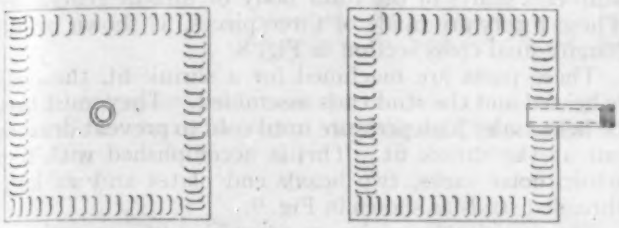


Fig. 6—The Nipple Through Which Hydraulic Pressure Is Applied Is Usually Located Either Centrally or at the Edge of the Pillow

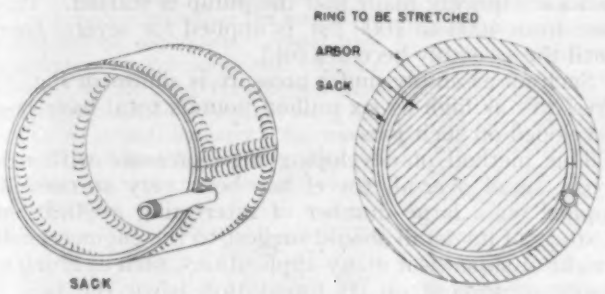


Fig. 7—Annular Structure for Exerting Radial Forces in Pressing Operations

Fig. 8—Schematic Representation of the Structure of a Large Rotor Whose Fabrication Was Simplified by the Use of Inflated Metal Pillows for Pressing in the Stub Shafts

Fig. 9—Components of the Pressing Equipment Employed in the Operation on the Rotor Assembly Shown in Fig. 8

The total pressure and travel obtainable from these sacks depends on the thickness of the material from which they are made, their area and the amount or thickness to which they are inflated. Those made from $^1/_8$-in. low-carbon steel and inflated to $^1/_2$ in. thickness withstood 10,000 psi. without failure. If the area of the sacks is relatively large, two may be used, one on top of the other, to increase the travel of the part being pressed. In some cases it is advisable to insert a relatively thick plate between them which makes the device more stable and maintains parallelism between the parts.

It is to be noted that, for safety, either water or oil must always be used to inflate the sacks; with the occurrence of failure the pressure is relieved immediately. Air, which is compressible, should never be used. As an

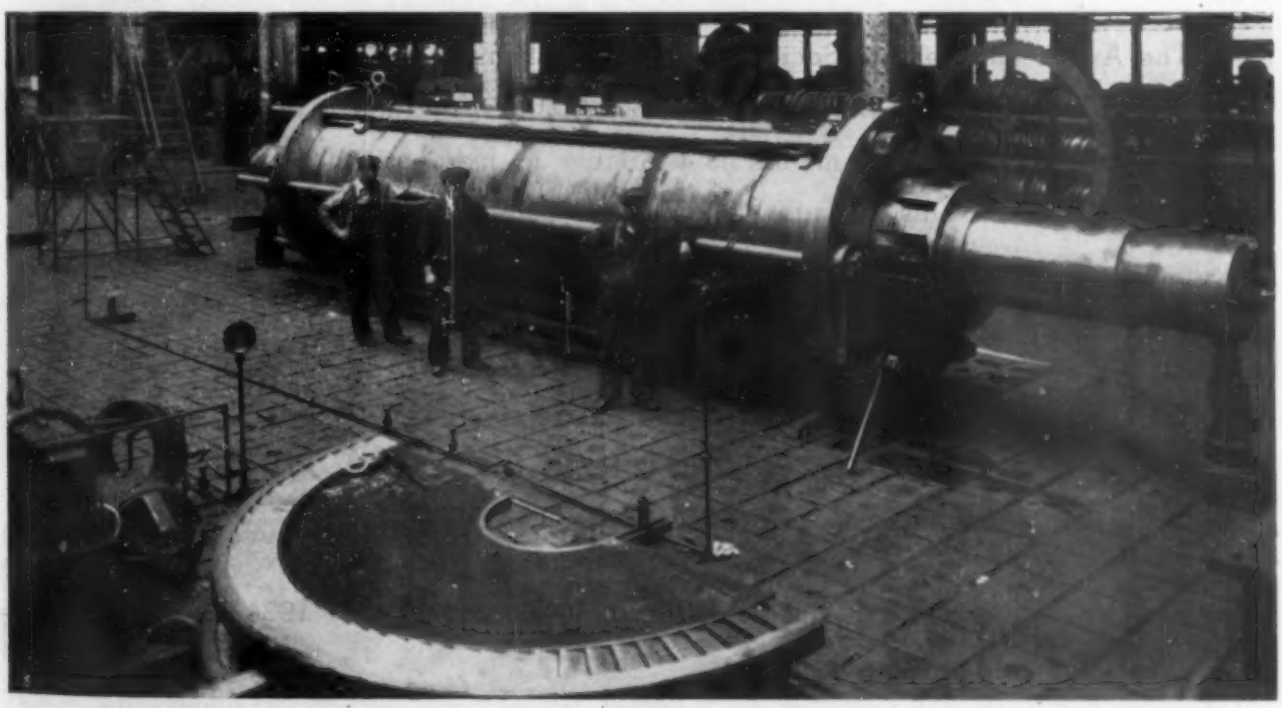


Fig. 10—Pressing Equipment in Place for Applying Forces in the Assembly of the Rotor

inflating medium it might cause serious trouble during a failure because there would be no immediate relief from the pressure.

Although the nipple for applying pressure may be attached anywhere on the surface or around the edge of a sack of any shape, the two most commonly used nipple positions are shown in Fig. 6. If, however, the nipple is to be put on an edge, the following procedure should be noted. The two sides of the sack should first be welded, then a hole drilled through the seam weld, centered on a line between the two sheets. After the nipple has been fitted or machined out to straddle the two sheets, it is centered over the hole and welded in place. Care should be taken that the welds penetrate deeply enough to prevent leakage through the seam weld.

A ring of considerable breadth may be cold worked by stretching to improve its physical strength, as shown in Fig. 7. Stretching may be applied for other purposes as well, such as for the enlargement of a forged ring that may be slightly undersize.

All the sacks can be made by the method shown in Fig. 2 and may be made of ordinary low-carbon steel, Everdur, stainless steel or other material which may be readily seam welded. The metal thickness may range from 0.015 to 0.125 in. in thickness.

When a weld is being made, care should be taken that the metal is carefully cleaned and properly welded. Tests should be made on small samples such as shown in Fig. 4 to prove the strength of welds before proceeding with the full-size sacks.

Generally speaking, these sacks should be used only once, because the metal near the weld where the maximum deformation takes place may become fatigued if sacks are flattened and reused, and failure might occur on subsequent use. The cost of these sacks is so low that there is usually no incentive for taking a chance on their reuse.

Figures 8, 9 and 10 show a factory application of the pressure sack as a shafting press in the pressing of stub-end shafts in the rotor body of turbine-generators. These rotors are made of three pieces, as shown by the longitudinal cross section in Fig. 8.

These parts are machined for a shrink fit, the body is heated and the stud ends assembled. They must then be held under high pressure until cold to prevent drawing out at the shrink fit. This is accomplished with four semicircular sacks, two heavy end plates and six long, threaded studs as shown in Fig. 9.

The semicircular sacks are assembled two on each end ring, the stud ends fitted to the heated rotor body, the end rings with sacks then placed in position and drawn tight with the six bolts. Hydraulic connections to the sacks are quickly made and the pump is started. Pressure from 4000 to 7000 psi. is applied for several hours until the assembly becomes cold.

Such an assembly under pressure is shown in Fig. 10. Pressures as high as six million pounds total have been developed on such jobs.

This method of developing high pressure with relatively small over-all travel has been very successfully applied on a large number of interesting applications. A study of its detail should suggest to the engineer, millwright or supervisor many applications, such as lining up heavy equipment on its foundation when the lack of space prohibits the use of jackscrews or other standard pressure or lifting devices.

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The Radiography of Spot Welds in Light Alloy and Ferrous Sheet Materials

By Robert C. McMaster* and Frederick C. Lindvall†

Introduction

RADIOGRAPHY has been found to be a sensitive nondestructive test of spot welds in many sheet materials. It provides information useful both in spot-weld process control and in the inspection of spot-welded assemblies. Rapid new X-ray exposure techniques and recently developed methods of interpreting weld properties from radiographs are being applied in the aircraft industry. The use of spot-weld radiography is expanding in accordance with the requirements of new specifications.

Certain aluminum alloys are ideal from the standpoint of spot-weld radiography.‡ Radiographs of spot welds in these alloys reveal clearly the weld structure, strength, and quality. Not all aluminum alloys, and few if any ferrous alloys, provide equally informative spot-weld radiographs. Yet in nearly all sheet materials, radiography provides sufficient information to be of value in spot-weld process control.

It is important, particularly in new industrial applications, that spot-weld radiography be used for appropriate purposes in suitable materials within the scope of its demonstrated sensitivity. This paper indicates the useful range of application of spot-weld radiography in light-alloy and ferrous sheet materials. It presents a summary of tests of spot-weld radiography in the following sheet materials: 24S-T Alclad, 75S-T Alclad, 61S-T, 61S-W, 52S-1/4H and 3S-O aluminum alloys; J1-H and 52S magnesium alloys; 1010 zinc-coated, 1020, annealed and full-hard 18-8 stainless and cadmium-plated X 4130 steels; Terne plate; and Inconel. Typical radiographs and corresponding weld sections are shown for each material. The spot-weld properties revealed by the radiographs are listed in each case.

In addition, fundamental principles are presented to explain the ability of spot-weld radiography to reveal weld properties in the various materials. With these principles in mind, it is possible to make reasonably useful predictions of the suitability of new materials for spot-weld radiography.

* Dr. McMaster, formerly Supervisor of Aircraft Welding and X-ray War Research Projects at California Institute of Technology, is now Assistant Research Supervisor at Battelle Memorial Institute in Columbus, Ohio.

† Professor Lindvall, who served as Official Investigator of NDRC, Project NRC-56, is Chairman, Division of Engineering, California Institute of Technology.

‡ "The Interpretation of Radiographs of Spot welds in Alclad 24S-T and 75S-T Aluminum Alloys," by Robert C. McMaster and Frederick C. Lindvall, in THE WELDING JOURNAL, 25 (8) 707–723, 1946. The bibliography of this paper lists additional references on spot-weld radiography.

The Causes of X-ray Images of Spot Welds

Radiographic images of spot welds are produced by irradiating the welded sheets with a practically uniform field of high-intensity, low-voltage X-rays from a source with low inherent filtration. Relatively few of the incident rays actually pass through the sheet material to produce the radiographic image of the weld region on the X-ray film. Most of the X-rays are absorbed in the material being radiographed. The X-ray image of the spot weld is produced because the X-rays are not absorbed uniformly throughout the entire exposure area. Differential X-ray absorption between adjacent areas of the spot-welded sheet material occurs for three basic reasons. These factors which produce the spot-weld images are: (1) Variations in the total thickness of the sheet material, (2) variations in material composition and structure and (3) variations in the geometry of inhomogeneous layers such as cladding on sheet materials.

Variations in Material Thickness

Minute differences in the total thickness of the material through which the X-rays pass occur as a result of internal voids, displacement of heated material under welding pressure, sheet indentation

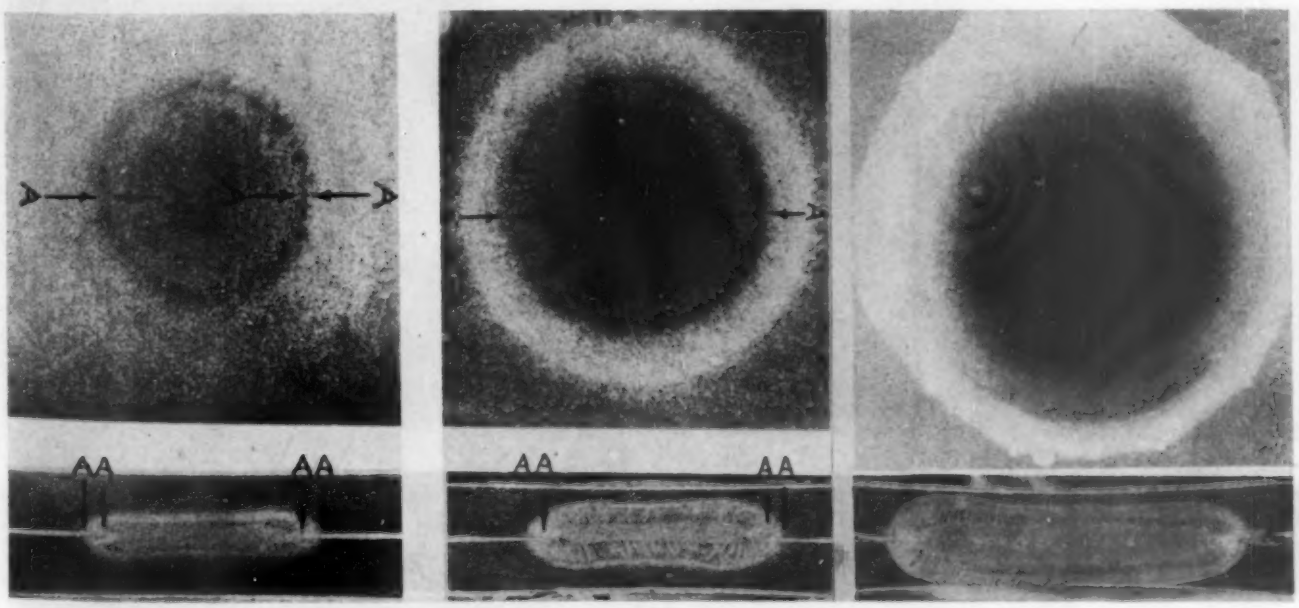

Fig. 1—Radiographs and Sections of Low-Energy, Normal and High-Energy Spot Welds in 0.040–0.040-In. 24S-T Alclad Aluminum Alloy Sheets

and similar conditions. The X-ray images of these minute differences in total material thickness are not a function of the composition or structure of the materials in the weld region. They result, instead, purely from the volume (mass) and location of the material and the interstices. Such images of differences in the total thickness of material in the X-ray beam may be obtained for spot welds in any material, regardless of composition or structure.

The following spot-weld properties are shown clearly on a spot-weld radiographs because they cause differences in the material thickness:

1. Cracking in the weld nugget.
2. Porosity in the weld nugget.
3. Expulsion of cast alloy from the nugget at the interface ("spit").
4. Extrusion of the nugget at the faying plane (usually the cause of excessive sheet separation).

With appropriate radiographic technique, these spot-weld properties can be shown more clearly and sensitively in X-ray images than by any other nondestructive or destructive method of examination now available. They may be shown equally well by radiography for any spot-welded sheet material.

Variations in Material Composition and Structure

Local differences in composition and structure of the material may produce X-ray images even in the absence of thickness changes. This situation exists when constituents with markedly different abilities to absorb X-rays are segregated in the weld region. If constituents which are relatively transparent to X-rays are segregated in one local region, the increased local X-ray transmission results in a dark, or heavily exposed, image of that region on the X-ray film. If highly absorbing constituents segregate, their image on the X-ray film will be lighter (less dense) than the average film density below the unaffected material. Obviously, the clarity and contrast with which composition and structure are revealed by such images depend critically upon the geometry of the segregations, and upon the relative differences in X-ray absorption and the relative amounts of each constituent present in the original material.

Alloys, such as 24S-T and 75S-T aluminum alloys, tend to show clear radiographic images of spot-weld structure and segregation. They contain relatively large amounts of radiographically dense alloying constituents such as copper and zinc. The balance of the parent material is for the most part aluminum, which is relatively transparent to X-rays.

On the other hand, nearly pure aluminum alloys, such as 3S-O, have only a small percentage of impurities and other alloying constituents. Differential X-ray absorption as a result of composition or segregation is very difficult to observe in these materials. Similarly, in most ferrous sheet materials, the X-ray absorption property of the common alloying constituents is not distinguishable, for small amounts of alloying material, from the X-ray absorption in the iron. Radiographs of spot welds in steel sheets seldom reveal sharp boundaries of segregation or structure. The spot-weld nugget, which differs from the parent material only in composition or structure (if it contains no voids), will not be revealed clearly in this class of materials.

The following spot-weld properties are shown clearly on spot-weld radiographs only when the parent material contains a significant percentage of a minor constituent which is radiographically different in density from the major constituent of the alloy and which migrates or segregates during the formation of the spot weld:

1. The boundary between the spot-weld nugget and the parent material. (This feature reveals absence of the weld nugget, undersize, normal or oversize weld nuggets, doughnut or cresent-shaped weld nuggets, misshapen weld nuggets and weld strength).

2. Segregation of radiographically dense constituents in the parent material. (The extent and location of segregation of eutectic in some aluminum alloys are a sensitive indicator of welding heat and of the extent of the heat-affected zone in the parent material.)

3. Structure and segregation within the weld nugget. (No correlation between nugget structure or segregation and spot-weld strength has as yet been shown to exist.)

Radiographic images of these weld features occur because spot welding causes a redistribution of the minor alloying constituents, so that they are no longer distributed uniformly throughout the parent material. In most alloys, high radiographic contrast sensitivity is required to reveal such redistributions of alloying constituents. In nearly pure aluminum alloys and in ferrous sheets it is extremely difficult to reveal these features clearly and reliably.

Materials with Inhomogeneous Layers

Some of the sheet materials commonly spot welded are not homogeneous throughout the entire thickness of the sheets. Alclad aluminum alloys are a typical example. The nearly pure aluminum cladding material is much more transparent to X-rays than the alloyed core material. Any redistribution in the location of the pure aluminum in the cladding will tend to be revealed clearly on the spot-weld radiograph. The nugget bound-

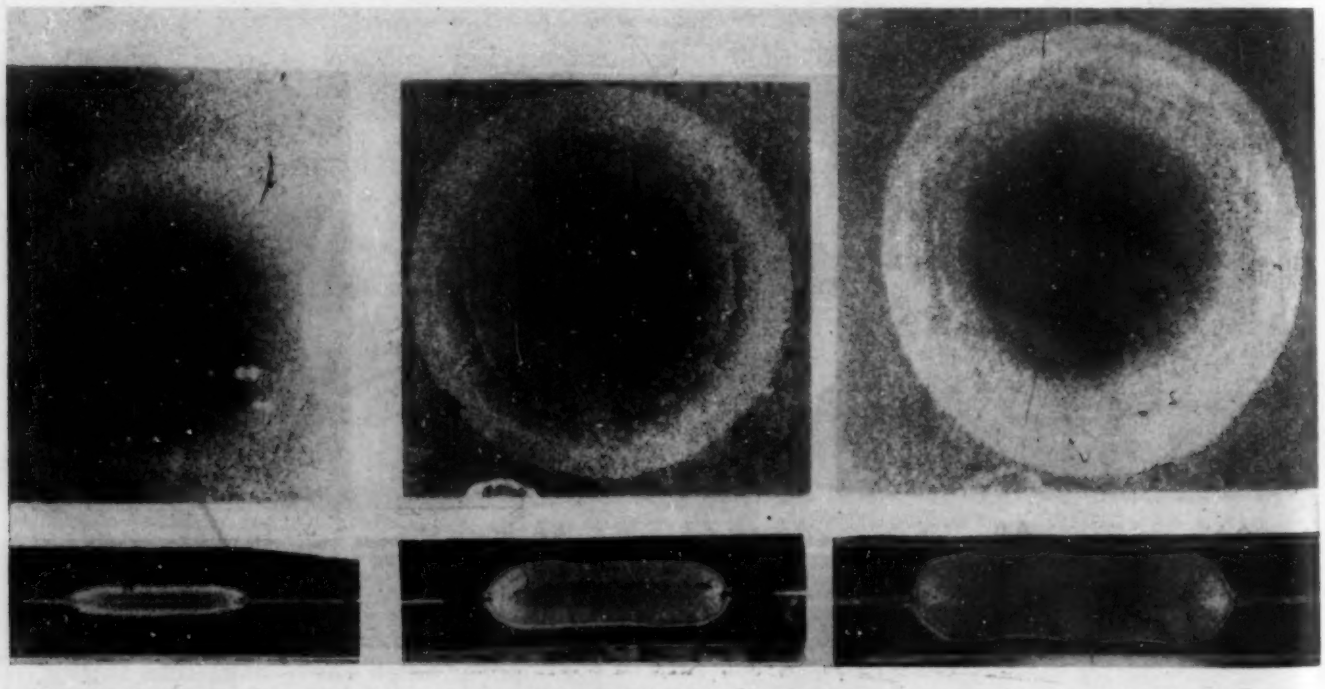

Fig. 2—Radiographs and Sections of Low-Energy, Normal and High-Energy Spot Welds in 0.040–0.040-In. 75S-T Alclad Aluminum Alloy Sheets

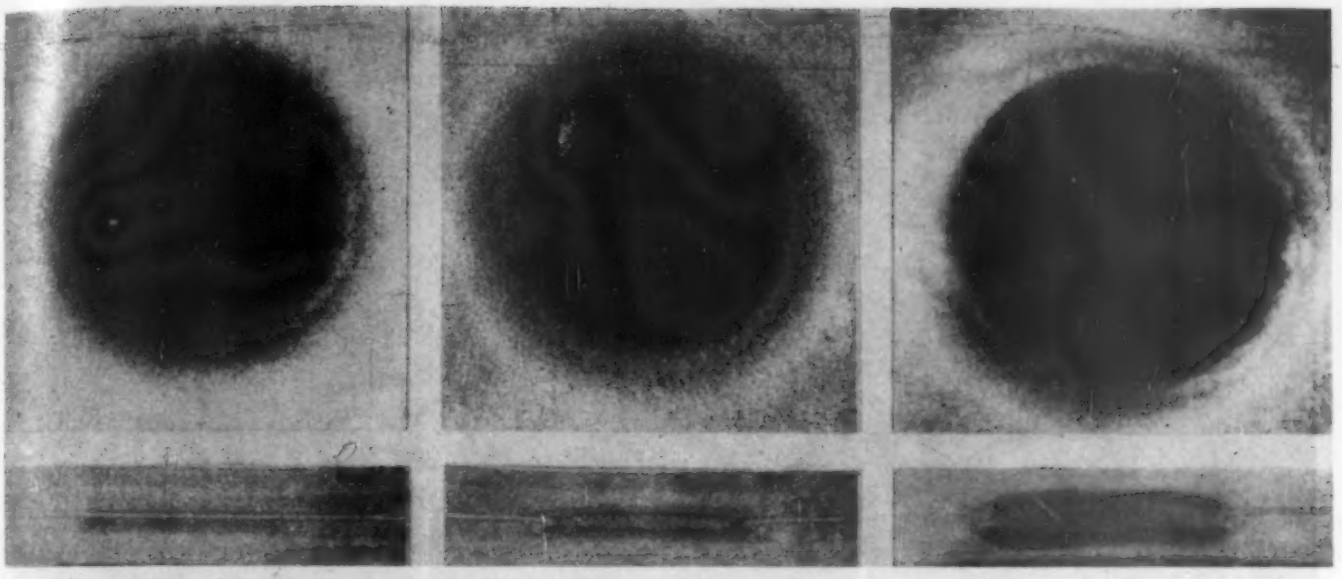

Fig. 3—Radiographs and Sections of "Dud" Weld, Low-Energy Weld and Normal Spot Welds in 0.040–0.040-In. 24S-O Alclad Aluminum Alloy Sheets

ary may be shown more distinctly because the cladding alloys with the core material only in the cast-alloy nugget. This leaves the Alclad inclusion in the weld nugget sharply defined. Welding heat and pressure also displace the cladding material in the corona region of the interface, changing the cladding thickness and revealing the corona boundary.

On the other hand, the lead coating on the surface of terne plate is radiographically more dense than the core material. When the lead coating is displaced from the nugget region as the spot weld forms, the lead may outline the nugget region at the faying plane. The radiographic image is reversed from that typically obtained with Alclad aluminum alloys. Zinc-coated steel sheets, however, show no such distinct images of weld nuggets, for the zinc has a radiographic absorption insufficiently different from that of the steel to produce a clear image, particularly with very thin layers of zinc.

The following spot-weld properties are shown on spot-weld radiographs because of the destruction or displacement of portions of inhomogeneous layers which have X-ray transparencies differing from that of the parent material:

1. Inclusion of cladding material into the cast-alloy weld nugget.
2. Corona region boundary.

The following spot-weld property is revealed on the spot-weld radiograph because radiographically dense material from an external source alloys itself with the sheet material: (1) Tip pickup.

Radiographs of Spot Welds in Various Sheet Materials

The following examples of spot-weld radiographs in various sheet materials reveal the suitability of these materials for spot-weld radiography. The advantages and limitations of radiography are clearly evident in these cases.

24S-T Alclad Aluminum Alloy

Figure 1 shows radiographs and sections of low-energy, normal, and high-energy spot welds in 0.040–0.040-in. 24S-T Alclad aluminum alloy sheets.* The prominent dark ring *A-A* outlines the nugget periphery and indicates the area of cast-alloy

* The interpretation of radiographs of spot-welds in Alclad 24S-T and 75S-T aluminum alloy is discussed in more detail in the preceding paper

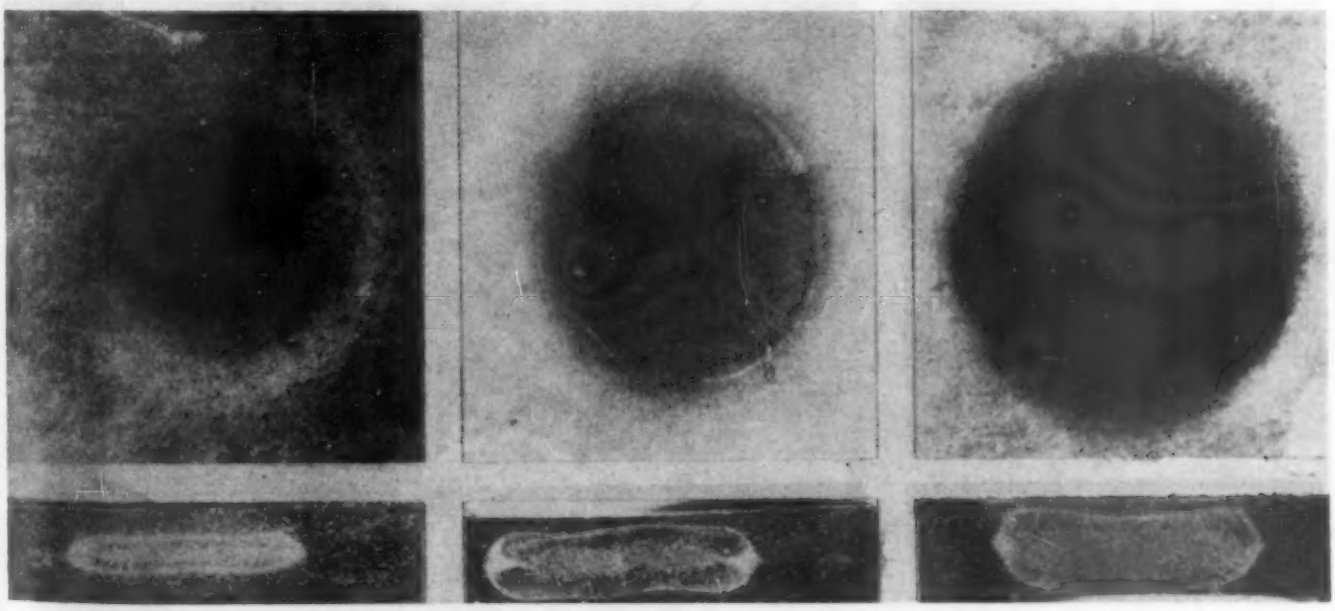

Fig. 4—Radiographs and Sections of Low-Energy, Normal (Cracked) and High-Energy Spot Welds in 0.040–0.040-In. 24S-T Bare Aluminum Alloy Sheets

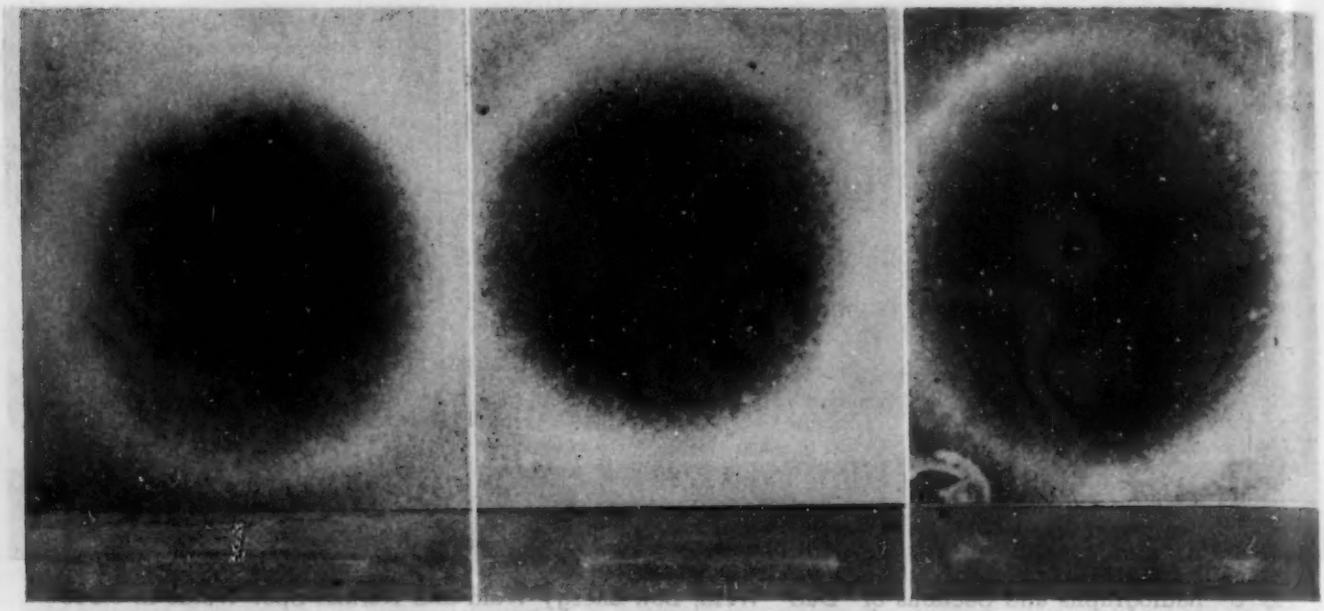

Fig. 5—Radiographs and Sections of Low-Energy, Normal and High-Energy Spot Welds in 0.040–0.040-In. 61S-W Aluminum Alloy Sheets

bonding at the faying plane. Weld strength can be predicted reliably from these radiographs. In general, such radiographs show positive indications of absence of weld nugget, undersize weld nuggets, excessive Alclad inclusion at the faying plane, cracking in the weld nugget, porosity in the weld nugget, segregation of eutectic in the parent material, expulsion or extrusion of the nugget at the faying plane, oversize or misshapen weld nuggets and tip pickup. The boundary of the corona ring is shown clearly. Alclad 24S-T aluminum alloy is an ideal sheet material in which spotweld radiography provides complete information concerning weld strength and properties. Radiography may be used reliably both in process control and in spot weld inspection.

75S-T Alclad Aluminum Alloy

Radiographs and sections of spot welds in 0.040–0.040-in. 75S-T Alclad aluminum alloy sheets are shown in Fig. 2. Like 24S-T Alclad, this sheet material is ideal for spot-weld radiography. Weld strength and all of the previously listed weld properties are revealed clearly in radiographs, in the same manner as with 24S-T Alclad. The same methods of interpretation may be used. Radiography is an excellent tool both for spot-weld process control and for inspection of spot welds in 75S-T Alclad.

24S-O Alclad Aluminum Alloy

As shown by the corresponding radiographs and section macrographs of Fig. 3, 24S-O Alclad aluminum alloy results in spot-weld radiographic images with a prominent dark ring and other features characteristic of 24S-T Alclad aluminum alloy. The usual weld defects such as porosity, cracking, expulsion, extrusion, undersize, oversize, misshapen, doughnut or crescent weld nuggets, excessive segregation of eutectic, excessive Alclad inclusion and tip pickup are revealed. In the particular specimens shown, the dark rings were broad, and the weld nuggets thin, frequently being centered below

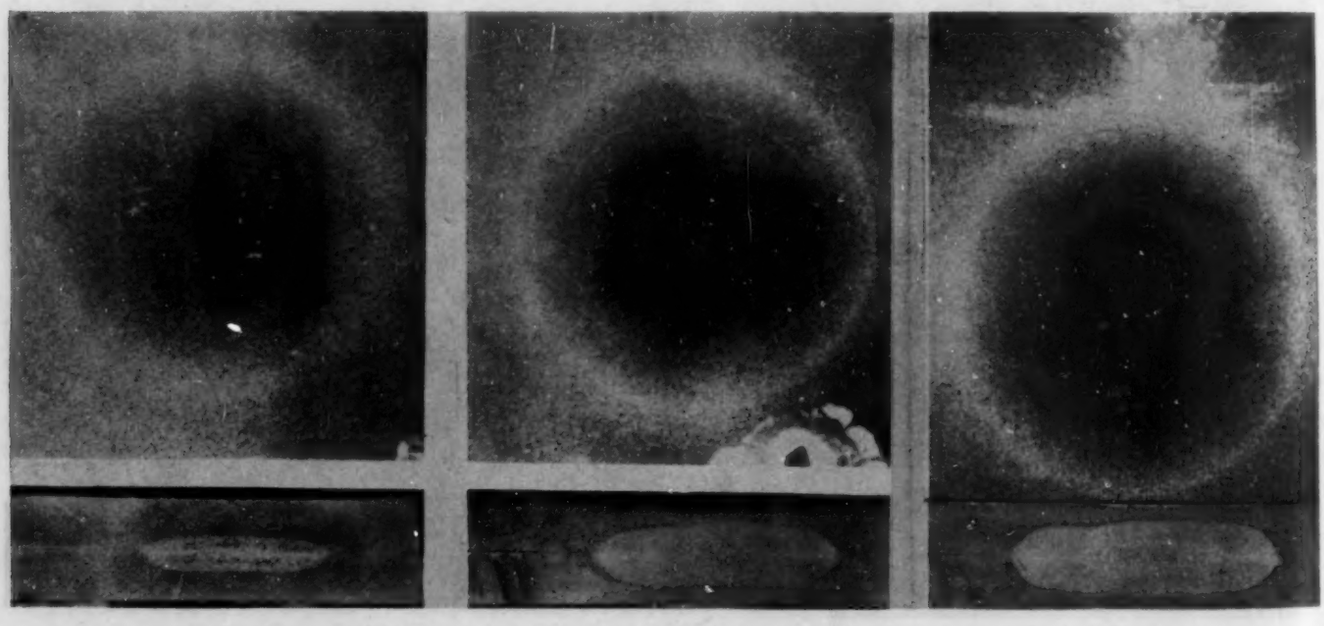

Fig. 6—Radiographs and Sections of Low-Energy, Normal and High-Energy Spot Welds in 0.040–0.040-In. 61S-T Aluminum Alloy Sheets

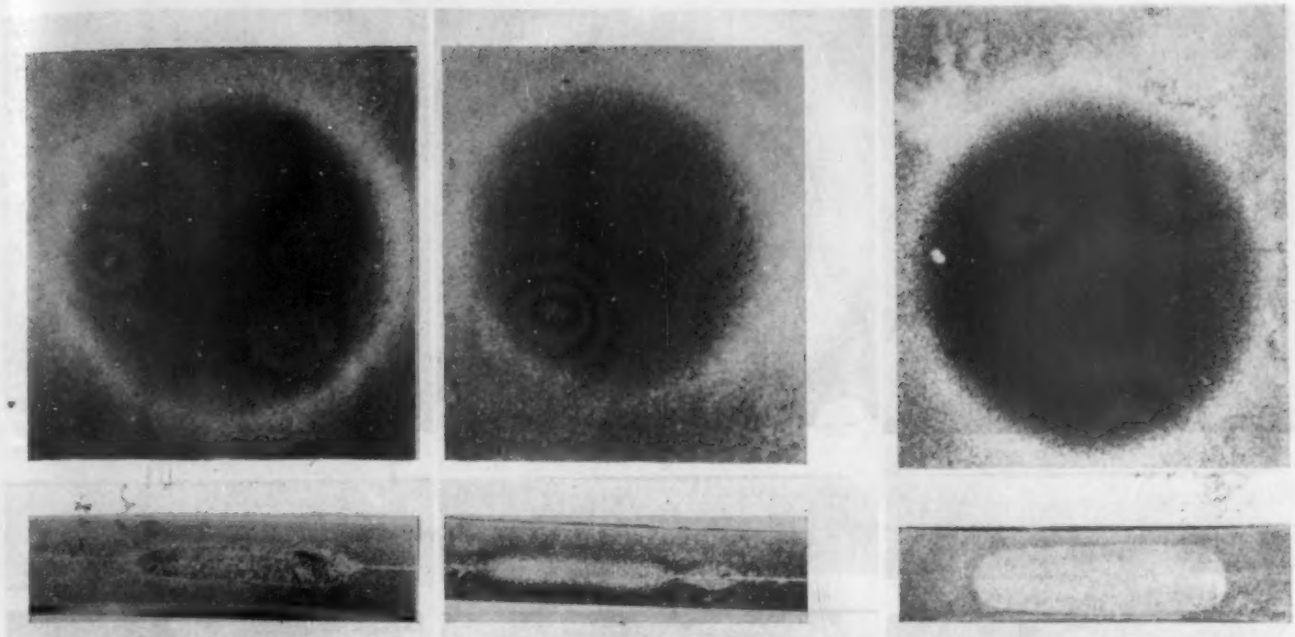

Fig. 7—Radiographs and Sections of Normal, Low-Energy and High-Energy Spot Welds in 0.040–0.040-In. 52S-$^1/_4$H Aluminum Alloy Sheets

the faying plane. These conditions would not necessarily be typical of a well-developed production technique of welding. In the static shear pull tests, the test strips, being relatively soft, bent so that, for the stronger welds, a large tension component of load was applied before failure. As a result, there was little variation in the load required for failure as nugget size increased, so no useful correlation between strength and radiographic dark ring could be obtained.

24S-T Bare Aluminum Alloy

Figure 4 shows corresponding radiographs and section macrographs of typical spot welds in 24S-T bare aluminum alloy sheets. It is evident that many of the properties of radiographic images of spot welds in 24S-T Alclad material are retained. For the thinner nuggets, absence of the Alclad layer at the interface causes the dark ring to be less prominent than with Alclad material. However, with the thick nuggets, the dark ring is broad and prominent, just as was the case in 24S-T Alclad for large nuggets with little or no Alclad inclusion. Correlation tests indicated that weld strength could be predicted reliably from the area within the radiographic dark ring. All of the weld defects (save excessive Alclad inclusion and prominent corona images) visible in radiographs of 24S-T Alclad spot welds are also apparent in radiographs of spot welds in bare 24S-T aluminum alloy.

61S-W Aluminum Alloy

In contrast to the preceding sheet materials, 61S-W aluminum alloy lacks radiographically dense alloying constituents in amounts sufficient to produce sharp, high-contrast radiographic images of spot-weld nuggets. As shown by Fig. 5, the radiographs reveal only a dark central region which fades gradually into a lighter outer ring, with no sharp delineation of the nugget boundary. Only on

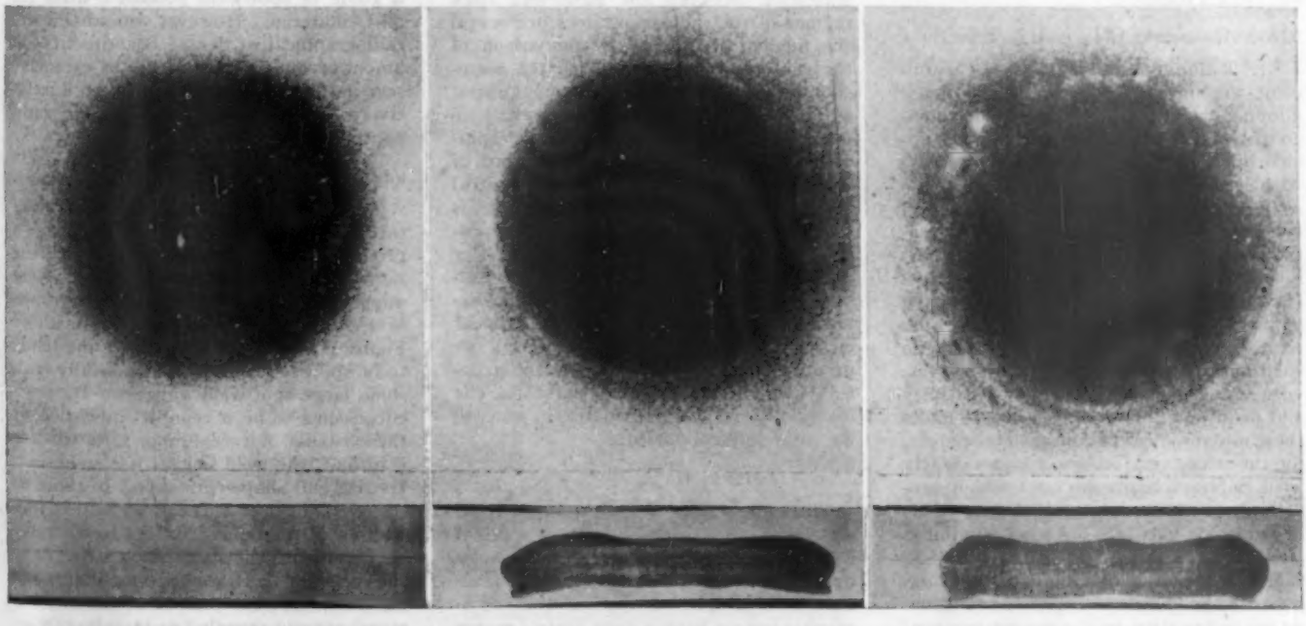

Fig. 8—Radiographs and Sections of "Dud," Normal-Energy and High-Energy Spot Welds in 0.040–0.040-In. 3S-O Aluminum Alloy Sheets

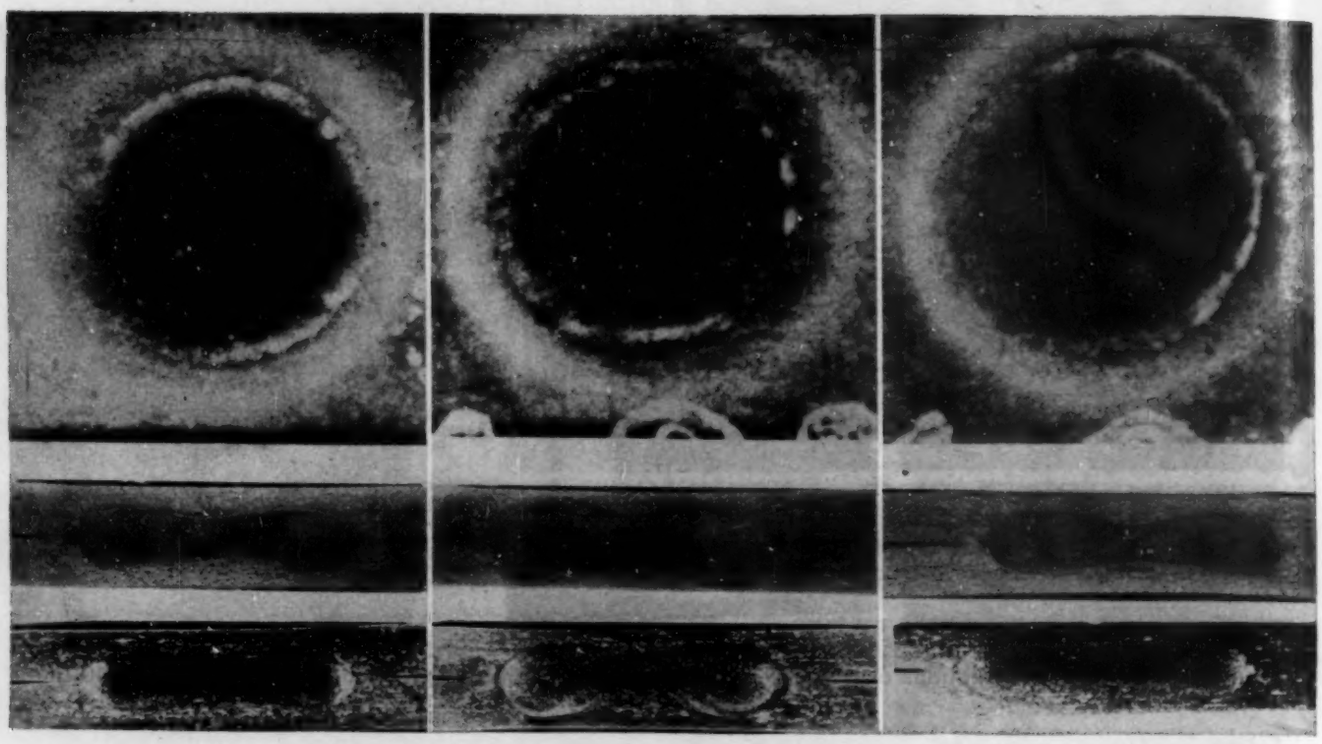

Fig. 9—Radiographs, Section Macrographs and Section Radiographs of Spot Welds in 0.040–0.040-In. J1H Magnesium Alloy

large spot-weld nuggets is the segregation sufficient to show any clear evidence of the nugget boundary or of local concentration of radiographically dense segregations in the parent material. Cracking, porosity, inclusions, expulsion, extrusion, severe segregation in the parent material and tip pickup are revealed when present. It has not been demonstrated that spot-weld strength can be estimated reliably from the radiographs, although with larger nuggets the segregation rings visible in the radiographs may give a clue concerning the nugget diameter.

61S-T Aluminum Alloy

61S-T aluminum alloy also lacks a sufficient amount of radiographically dense alloying constituents to result in high-contrast spot-weld images. With sufficiently large nuggets, a faint white ring with very little width appears on the radiographs. As shown by a comparison of the radiographs with section macrographs in Fig. 6, this white ring does correlate with the nugget diameter and shape. If revealed clearly on the radiograph, the white ring may be measured and the area within it taken as being indicative of the weld nugget size and strength. However, very high radiographic contrast sensitivity and definition would be required to make these measurements a practical procedure, for the white ring seldom appears clearly with radiographic techniques which produce very excellent images of spot welds in materials like 24S-T Alclad aluminum alloy. Radiographs of spot welds in 61S-T aluminum alloy also reveal cracking, porosity, inclusions, expulsion, extrusion, severe segregation in the parent material and tip pickup when these conditions exist in the welds. Radiography may be used in process control and, with improved radiographic techniques, might find application in spot-weld inspection with this alloy.

52S-$^1/_4$H Aluminum Alloy

52S-$^1/_4$H aluminum alloy produces spot-weld radiographic images with little or no detail which can be used reliably in predicting weld strength. As is evident in Fig. 7, the radiograph shows only a dark central region surrounded by a lighter ring with no sharp boundaries. The gradual transition between the light and dark regions of the radiograph does not reveal the nugget periphery, as comparison of the example radiographs with the corresponding weld sections demonstrates. With large, thick nuggets, some evidence of concentric segregation of radiographically dense materials occurs in the form of a faint light ring within the dark central area of the radiograph. This image is much too faint to be used in practical production inspection to reveal the diameter of the weld nugget or its strength. Evidences of cracking, porosity, expulsion, extrusion, inclusions, and tip pickup appear on the radiograph when these defects are present in the welds. Evidences of structure and local segregation (save for the features mentioned above) are, in general, too faint to be observed.

3S-O Aluminum Alloy

The radiographs of spot welds in 3S-O aluminum alloy sheets show little detail of weld structure and shape. As shown by the corresponding radiographs and section macrographs of Fig. 8, the radiographic images have a dark central region surrounded by a lighter area and may show faint rings or spots near the periphery of the nugget. However, these indications are so faint on the radiographs that it is not practical to use them for a measure of the spot-weld nugget size and strength. The density of the dark central region is not necessarily a reliable guide to nugget presence or size, for a surprisingly dark central area on the radiograph can be obtained on "welds" which have no nugget. Typical defects such as cracking, porosity, inclusions, expulsion, extrusion and tip pickup will be revealed when present, and to this extent radiography may be used as a guide in spot-weld process control for 3S-O material. However, the absence of radiographically dense constituents in amounts sufficient to result in extensive segregation images makes 3S-O a relatively unsatisfactory material for radiographic inspection of spot welds.

J1H Magnesium Alloy

J1H magnesium alloy produces rather satisfactory spot-weld images in which a prominent white ring occurs in much the same location with respect to the weld nugget as does the dark ring in radiographs of spot welds in 24S-T aluminum alloy. Figure 9 shows that this white ring tends to be spotty and to disappear locally with some large spot-weld nuggets. Its presence seems to be a reliable indication of the existence of a weld nugget, for when it is absent, the weld nugget is also absent. Its size and shape correspond to those of the weld nugget. The area within the white ring was found by test to correlate very well with the static shear strength of the spot welds. However, doughnut welds (of which several occurred in these specimens) are not revealed as prominently as might be desired. Very faint images of the "hole" in the doughnut nugget can be

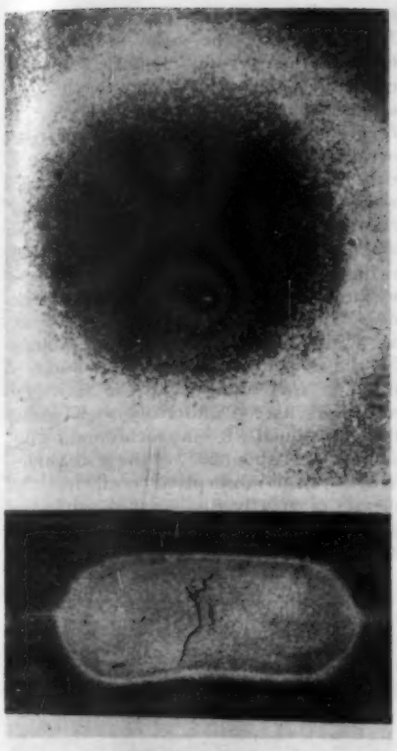

Fig. 10—Radiograph and Section of Normal Industrial Spot Weld in 0.040–0.040-In. 52S Magnesium Alloy Sheets

detected if the doughnut is known to be present; otherwise the indication is not easily observed. Typical defects such as undersize and oversize weld nuggets, cracking, porosity, inclusions, expulsion, extrusion, misshapen weld nuggets and tip pickup may be observed when present in the weld. Section radiographs reveal segregation of radiographically dense constituents near the periphery of the weld nugget and indicate that the white ring lies just inside the nugget boundary. Practical use might be made of radiography in both process control and in inspection of spot welds in J1H and similar magnesium alloys.

52S Magnesium Alloy

A few normal welds in 52S magnesium alloy were radiographed and sectioned. Figure 10 shows a typical radiograph and section macrograph. The radiograph reveals weld properties clearly, showing by rings the boundary between nugget and parent material, and showing by clear images the presence and extent of cracking, porosity, inclusions, expulsion, extrusion and tip pickup. Radiography could be used to predict spot-weld strength in 52S magnesium alloy if strength is (as in most other materials) proportional to the bonded nugget area at the faying plane. Radiography would be suitable for process control and for inspection of spot welds in 52S magnesium alloy.

Zinc-Coated 1010 Plain Carbon Steel

A few normal production spot welds in zinc-coated 1010 steel were radiographed and sectioned with the results shown in Fig. 11. The radiograph shows a gradual change in density from the center region of the nugget to the lighter ring over the parent material, but the nugget boundary is not shown sharply. Cracking, porosity, expulsion and extrusion would be shown clearly when present. The indentation of the sheets by the welding electrodes resulted in images which overlie those due to the weld nugget, in the example shown. Radiography might be used in process control, and possibly in inspection, but it would probably be difficult to measure weld strength from the radiographs. In this case the cladding material is not greatly different in radiographic density from the parent material. Its extremity is revealed only where cladding material has been expelled from the nugget region at the faying plane, increasing the total thickness of material and revealing the corona boundary.

Full-Hard 1020 Steel

Radiographs of normal welds in 1020

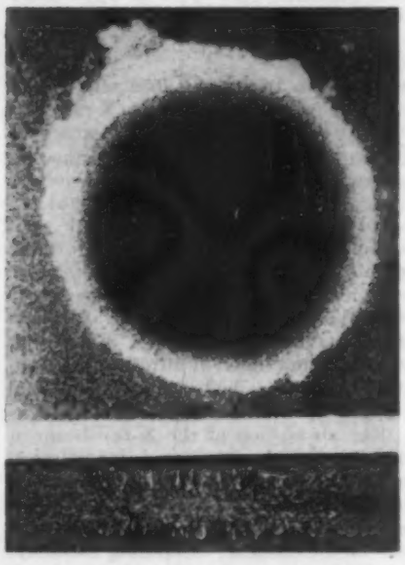

Fig. 11—Radiograph and Section of Normal Industrial Spot Weld in Zinc-Coated 1010 Plain-Carbon Steel

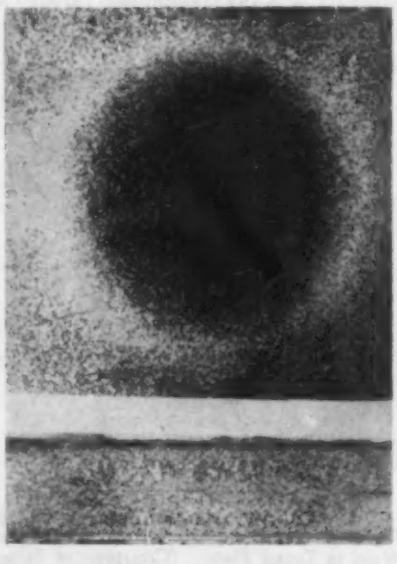

Fig. 12—Radiograph and Section of Spot Weld in Full-Hard 1020 Steel Sheets

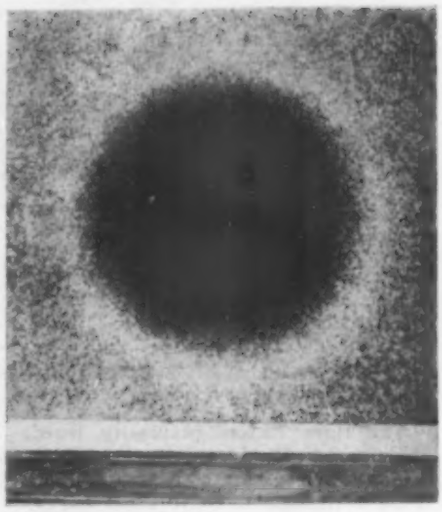

Fig. 13—Radiograph and Section of Spot Weld in Cadmium-Plated X 4130 Steel Sheets

steel reveal only a light ring surrounding the weld region, as shown in Fig. 12. Defects such as cracking, porosity, expulsion and extrusion would be shown when present. Radiography would be a useful guide in process control, but has not yet been proved to be a reliable indication of weld size or strength.

Cadmium-Plated X 4130 Steel

Figure 13 shows a radiograph of a normal weld in cadmium-plated X 4130 steel. It reveals only a gradual change from a dark central region to an outer light ring in the weld region. Defects such as cracking, porosity, expulsion and extrusion would be shown when present. The nugget diameter and strength probably could not be determined reliably from the radiograph.

18–8 Annealed Stainless Steel

Radiographs of normal spot welds in 18–8 annealed stainless steel show the usual dark central region surrounded by a lighter ring with no particularly sharp delineation of the nugget boundary. Figure 14 shows a typical radiograph and section macrograph. The same defects would be revealed as are listed for the preceding steels.

18–8 Full-Hard Stainless Steel

Figure 15 shows the radiographic properties of spot-welded full-hard stainless steel to be similar to those of annealed 18–8 stainless steel.

Terne Plate

The lead coating over plain-carbon steel in terne plate provides an interesting example of a cladding which is radiographically more dense than the core material. The radiograph of Fig. 16 reveals sharply the inner extremity of the cladding at the periphery of the nugget, as well as the outer extremity of the corona region in which the cladding is thickened. Complete tests have not been made, but the possibility exists that the nugget size and strength and perhaps all of the properties

visible in radiographs of spot welds in 24S-T Alclad aluminum alloy might be shown in radiographs of welds in terne plate.

Inconel

Figure 17 shows a typical radiograph of a normal spot weld in Inconel. The only detail revealed is a dark central region surrounded by a lighter ring, with no sharp indication of the nugget boundary. The usual defects such as cracking, porosity, expulsion and extrusion would be shown clearly.

Predicting the Suitability of Materials for Spot-weld Radiography

The three factors previously listed, namely: (1) differences in material thickness, (2) segregation of radiographically dense or transparent constituents and (3)

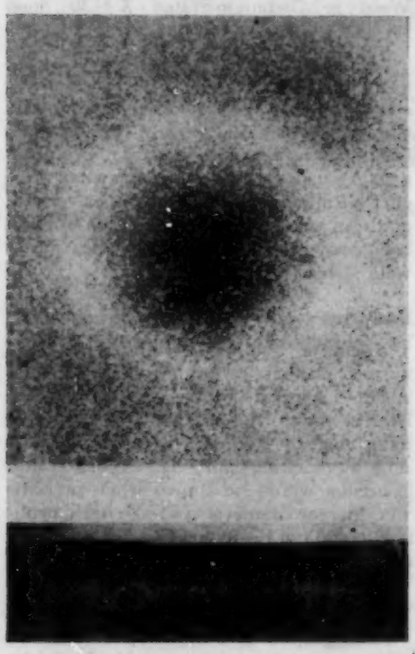

Fig. 14—Radiograph and Section of Normal Industrial Spot Weld in 0.031–0.031-In. 18–8 Annealed Stainless Steel Sheets

destruction or displacement of portions of layers in inhomogeneous sheets (when those layers have different X-ray transparency than the parent material), determine the quality of the spot-weld radiographic images. Of course, radiographic exposure and development techniques also play a major role in determining the contrast and definition in the radiographic image, and these factors will be discussed in greater detail in another paper. But excellent radiographic technique cannot compensate for the lack of an initial cause for differential absorption of X-rays in the welded sheets. Without the influence of the three basic factors, no X-ray images would result from spot welds.

The relative X-ray absorption powers of alloys can be estimated readily. The X-ray absorption power of an alloy depends solely upon the relative masses and the X-ray absorption properties (or "radiographic densities") of the individual con-

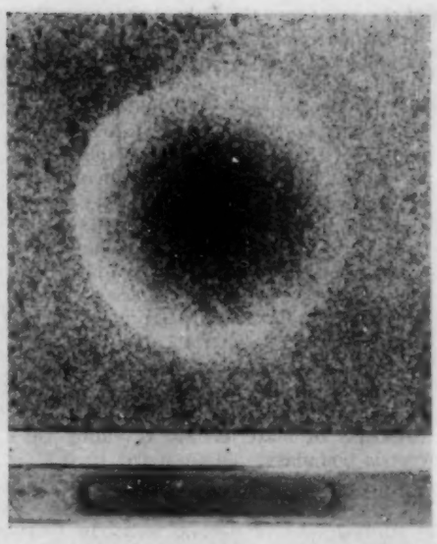

Fig. 15—Radiograph and Section of Normal Industrial Spot Weld in 0.014–0.014-In. 18–8 Full-Hard Stainless Steel Sheets

stituents in the alloy. The relative absorption values change with X-ray kilovoltage or wave length, and differences in absorption between constituents tend, in general, to increase as X-ray kilovoltage is lowered. So also does the total absorption in each material. For this reason, spot welds are usually radiographed at the lowest voltage at which sufficient X-rays will pass through the welded sheet to expose the X-ray film in a reasonable period of time. With X-ray sources of low inherent filtration, this condition produces high-contrast spot-weld images.

The absorption of the X-ray beam in an alloy may be duplicated (for practical measurements) by the absorption in a laminate of sheets of appropriate thicknesses, where each sheet is made of only one of the elements composing the alloy. If the X-ray opacity of each minor constituent is stated in terms of an equivalent thickness of the major constituent at a given X-ray voltage, then the relative intensity of X-ray transmission through a

Fig. 16—Radiograph of Industrial Spot Weld in Terne Plate. (Courtesy of John Haunty and Marshall Spangler of Curtiss-Wright Airplane Division, Columbus, Ohio)

thickness of the alloy can be estimated. Figure 18 gives the ratios of the X-ray opacities of several common alloying elements to that of aluminum for the same sheet thicknesses, throughout the voltage range commonly used in spot-weld radiography of light alloys.* The kvp.-tube voltages associated with these ratios were obtained by multiplying the monochromatic voltage values (taken from standard tables) by 1.7. The multiplication factor was determined experimentally by measuring the ratios of thickness for equivalent X-ray transmission at a number of values of tube voltage for the elements iron, aluminum and copper. It was found that the ratios, so measured, agreed uniformly with similar ratios obtained with monochromatic voltage values of about 59% of the peak values. When linear absorption coefficients of metals of greatly dissimilar densities are compared, the ratio is valid only for thin sections of the heavy metal. Ratios of

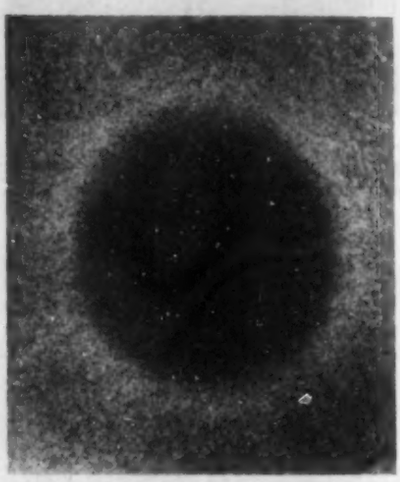

Fig. 17—Radiograph of Industrial Spot Weld in Inconel

the linear absorption coefficient of metals of similar densities apply, for practical purposes, to any thickness.

24S aluminum alloy will be taken as an example. The nominal composition is 93.4% aluminum, 4.5% copper, 0.6% manganese and 1.5% magnesium. The density is 0.100 pound per cubic inch. Assume that the spot-welded sheets of 24S have a total thickness of 0.1 in. The weight of the alloying elements in each square inch of the two sheets (0.1 in. total thickness) would be 0.00045 lb. of copper, 0.00006 lb. of manganese and 0.00015 lb. of magnesium. Sheets of copper, manganese and magnesium, each 1-in. square, having the above weights, would be 0.0014 in., 0.00022 in. and 0.0024 in. thick, respectively. Figure 19 (*A*) illustrates the relative thicknesses of each of these metals, on a weight basis.

Figure 18 indicates that at 30 kvp., a given thickness of copper will have an X-ray opacity equivalent to a thickness of aluminum 32 times as great. Therefore, at 30 kvp., the copper content of a 0.1-in.

* These data and the method of application are available through the courtesy of H. D. Roop of Los Angeles, X-ray consultant in this research

layer of 24S alloy has an X-ray absorption equivalent to that of 0.0470 in. of aluminum. Similarly, it is found that the manganese content is equivalent in X-ray absorption to 0.0004 in. of aluminum, and the magnesium is equivalent to 0.0014 in. of aluminum. The relative contribution to the total X-ray opacity of 24S alloy by each of the constituents is indicated in Fig. 19 (*B*). The effects of the magnesium and manganese contents are so small that they may be ignored.

As indicated by this example, the 4.5% by weight of copper in 24S alloy contributes approximately one-third of the total X-ray absorption or radiographic opacity. Relatively small percentage redistributions in the local concentration of copper as a result of spot welding, therefore, produce clear radiographic images. Where copper constituents segregate, the 32 times greater X-ray opacity in comparison with aluminum insures prominent images even when the volume of segregation is quite minute.

Unfortunately, from the standpoint of the spot-weld radiographer, the situation is quite different in 2S, 3S, 52S, 61S and similar alloys. In none of these alloys do the alloying constituents contribute more than a few per cent to the total X-ray opacity of the alloy. In some cases, the normal impurities in the aluminum account for most of the spot-weld image. Redistributions of small amounts of the alloying constituents are very difficult to detect in the spot-weld radiographs.

The prominence with which spot-weld structure, nugget boundary and segregations will be shown radiographically for any alloy may be estimated by the procedure illustrated above. Only in cases in which the minor alloying constituents contribute a significant portion of the total X-ray opacity of the alloy, and are subject to redistribution or segregation during spot welding, can good radiographic delineation of structure and segregation be expected.

In the case of clad sheets, the relative X-ray absorption properties of core and cladding materials may be estimated by the same procedure. Redistributions of cladding material will be shown prominently when the difference in absorption between core and cladding is large. However, those redistributions of cladding material which cause changes in the total thickness of the spot-welded sheets will

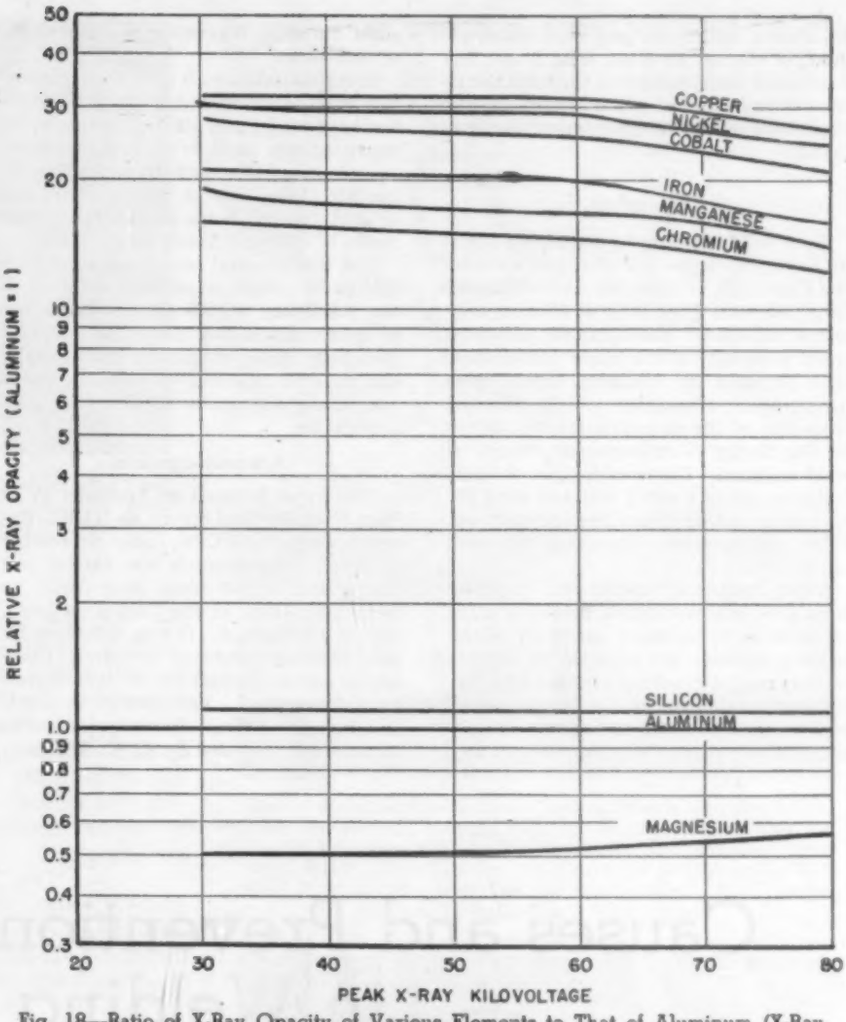

Fig. 18—Ratio of X-Ray Opacity of Various Elements to That of Aluminum (X-Ray Opacity of Aluminum = 1)

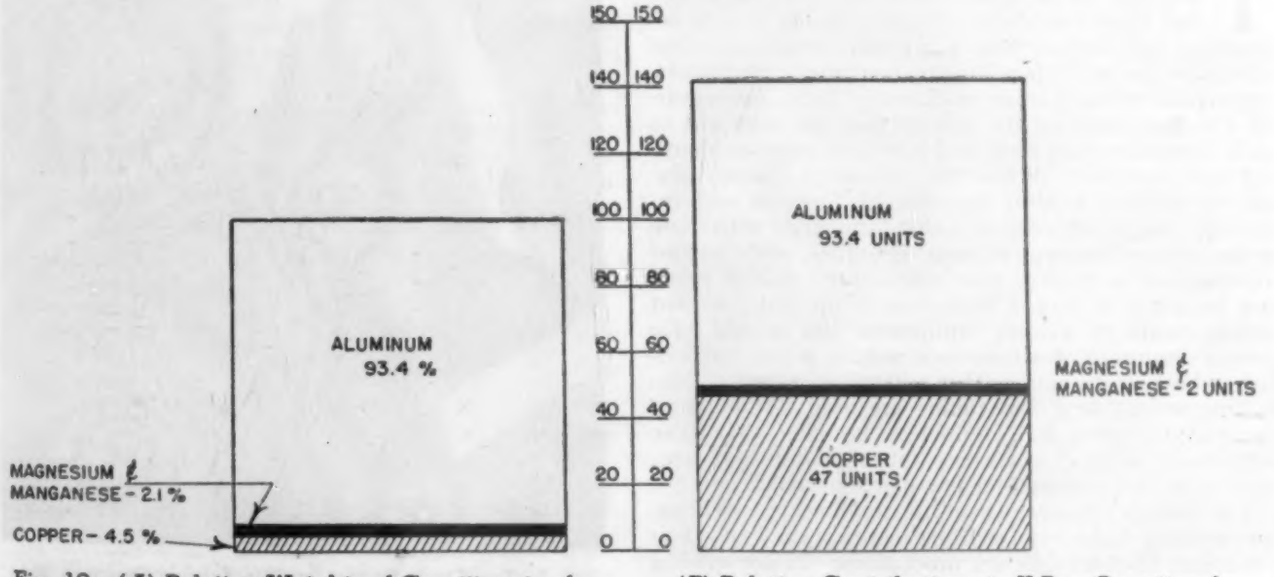

Fig. 19—(*A*) Relative Weights of Constituents of 24S Alloy (*B*) Relative Contributions to X-Ray Opacity of Constituents of 24S Alloy

be shown clearly in any clad material. And, of course, all other weld properties associated with changes in the total thickness of the material will be shown clearly regardless of the composition of the material.

Conclusions

Spot-weld radiography provides a sensitive nondestructive test of nugget size and weld strength in materials with relatively large amounts (2 to 8%) of alloying constituents whose radiographic densities differ from that of the major constituent. The presence of cladding layers with radiographic absorption widely different from that of the core material contributes to the clarity of radiographic images of weld nuggets. The combination of these features makes a sheet material ideal for spot-weld radiography, and permits reliable radiographic inspection of spot welds.

Most spot-weld conditions resulting from poor process control, improper sheet preparation or incorrect operation of the welding machine are revealed by defects such as nugget cracking and porosity, extrusion or expulsion at the faying plane, and tip pickup. The radiograph reveals these defects clearly for spot welds in any sheet material, regardless of composition or structure.

Sheet materials with very small quantities of alloying constituents, or with alloying constituents having radiographic opacities very close to that of the major constituent, seldom provide reliable radiographic indications of weld nugget size or weld strength, in the absence of cladding layers of different X-ray opacity.

The fundamental principles outlined in this paper permit an advance estimate of the possibility of radiographic inspection of spot welds in any particular material. New fields of use of spot-weld radiography can thus be explored without the losses and disappointments incident to misapplication.

Acknowledgments

This paper is based on Appendix IV of Part II of the final report on NDRC Research Project NRC-56, dated September 1, 1944. The research was carried out during the period from May 1943, to September 1944, at the California Institute of Technology. It was sponsored by the National Defense Research Committee and supervised by the War Metallurgy Committee. Professor F. C. Lindvall was the Official Investigator. The authors were assisted by C. C. Woolsey, metallurgist; J. W. Smith, X-ray engineer; L. P. Gaard, assistant project engineer; Edyth Dial, photographic supervisor; and C. E. Weaver, M. E. Breen, D. L. Bashore, G. M. Lansdell, C. L. McWade, L. J. Maguire, J. E. Haskell and A. Burdorf during the period of this research.

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Causes and Prevention of Defects in Welding

By Frederick S. Dever*

THE causes of defects in welding are usually preventable faults in technique or procedure. For this reason welded fabrication should not be rejected on the drafting board any more than any other fabrication method when done by competent fabricators, experienced or high-grade workmen. Ryan Aeronautical Co. has classified the defects that are most apt to occur in welding and indicated how they may be identified and prevented. While this knowledge is most valuable to welders, welding department foremen and inspectors, design engineers find that familiarity with these production problems gives more assurance, when welded construction is desired, that satisfactory welded joints can be made if proper technique is applied. Recent developments in welding equipment also should give greater assurance of satisfactory welded joints, particularly where electronic or other automatic means of controlling welded heat and timing are used. It must be recognized in using such equipment, however, that these refinements in machines necessitate operator skill comparable to that required for fine machine tools.

The defects encountered in arc welding, gas welding, spot welding and special welding methods vary and their correction involves different procedures. In arc welding lap, fillet and butt joints the common defects are likely

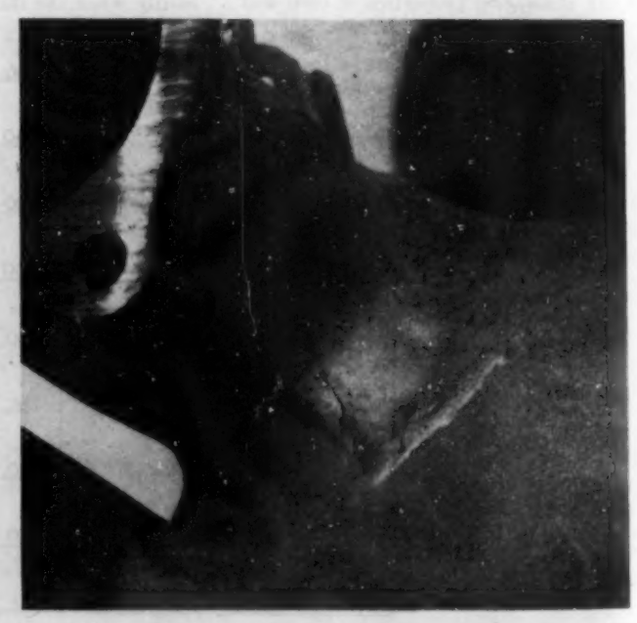

Fig. 1—The Crack Evident in This Exhaust Structure Was Caused by Too Rich a Flame Adjustment Which Deposited Carbon in the Weld and Caused the Metal to Become Brittle

* Welding Supervisor, The Ryan Aeronautical Co., San Diego, Calif.

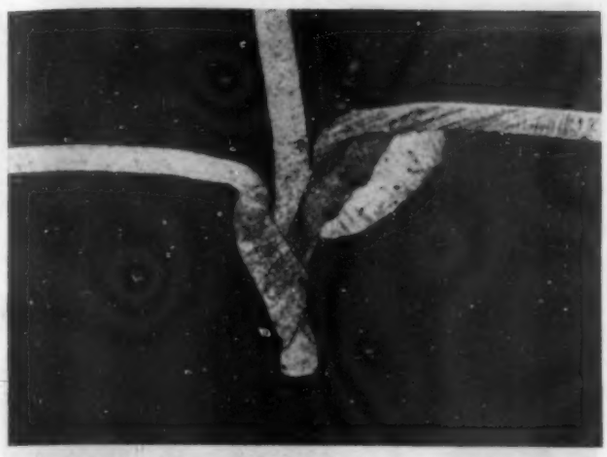

Fig. 2—Cutaway Section of a Stainless Steel Part Showing Poor Fusion Between the Weld and Parent Metal. This Is a Two-Pass Arc-Welding Job in Which the Flux Left by the First Weld Was Not Cleanly Removed

to be caused by poorly fitting the parts together, improper tack welding , lack of proper technique and application, or any combination of these. Metallic arc welding defects have been classified in 10 general groups.

1. "Burn-through," usually associated with lap welding, is defined as penetration exceeding 100%. This is sometimes not too serious. In 18–8 stainless steels, however, the oxidation produced destroys heat and corrosion resistance of the metal, which is one reason for identifying "burn-through" as a defect. There may be one or several causes for this defect.

A variation of welding speed to compensate for excessive gaps in poorly fitted parts will cause burn-through because the heat input is excessive in these areas where a large amount of weld metal is required to fill the gaps in the joint.

If voltage and amperage are too high for the metal thickness being welded, the resulting excessive heat will cause burn-through. If the rate of travel or welding speed is too slow or erratic (fast and slow), burn-through may result. The angle at which the electrode is held may contribute in causing this defect. In tacking, the use of extreme heat setting may result in small burn-through areas or large tacks, which the welder must fuse when completing the weld.

2. Overlap, often called a "cold weld," is a defect characterized by lack of fusion between parent metal and weld metal. It is usually small in area. Overlaps may be caused by too low voltage or amperage, too fast travel of electrode, flux on tack welds, excessive scale on parts, flux from electrodes "getting ahead" of weld metal deposit, peculiar flux action caused by incorrect angle of electrode, or by large "cold" tacks that do not fuse with the finish weld.

3. Skips or omissions refer to incompleted welds at certain points. Improper positioning of a part to be welded can cause this defect, especially if the welder does not have a complete view of the weld area. Other causes are flux from tacks, or flux "balling up" during welding, erratic speed of electrode travel, poorly fitted parts, defective spot-weld tacking, lack of care inside 90° corners, or poorly fluxed electrodes, which cause a "wild" or unstable arc. Also the welder may be affected by sudden disturbing noises or his helmet lens may be too dark to give good vision of the weld "puddle" while depositing metal.

4. Cracks are not characteristic of the metallic arc process when using 18–8 stabilized electrodes. This de-

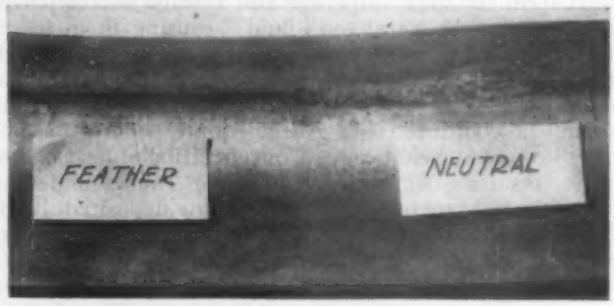

Fig. 4—Stainless Steel Exhaust Section Which Was Welded by Both Feather and Neutral Flames. Feather Flame Was Too Rich in Acetylene and as a Result Carbon Was Deposited in the Weld Metal. This Lowered the Corrosion Resistance So That Acid Pickling Bath Dissolved the Weld Metal. With Neutral Flame, No Acid Attack Was Evident

Fig. 3—Close-up of a Blowhole Defect in Spot-Welded Area. This Was Caused by Improper Machine Setup with Misaligned Electrode Tips and Uneven Pressure. Metal Was Forced Out of the Space Between the Sheets by This Misdirected Pressure

Fig. 5—Feminine Ryan Welder Seam Welds a Gastight Structure by Means of Overlapping Spot Welds

fect is more apt to occur in high-carbon steels and alloy steels such as X4130 and 25–12 stainless, especially if the assembly contains heavy cross-sectional fittings or plate, or light tubes. Thermal stresses set up during welding are sufficient to cause cracks.

The commonest causes of cracking in 18–8 stainless are excessive cold working of the material, including forming and bending, after welding, extremes in light- to heavy-gage combinations, which cause shrinkage stresses, incorrect welding procedure and shear or tension loadings while the weld area is at 1200 to 1600° F., the "hot short" temperature.

5. An undercut is a defect in which the weld metal deposit leaves a notch on one or both sides of the weld bead and is insufficient to fill the crater in the joint. Concentration of stresses in these notches is, of course, serious.

There are four leading causes of undercuts. Excessive heat from the high amperage and voltage makes parent metal and weld metal too "fluid," causing them to sag under the influence of gravity. If the rate of electrode travel is too fast, insufficient weld metal is left to fill the crater left by the heat of the arc. These two conditions should be coordinated to give adequate penetration and a well-rounded weld bead. Concentration of heat on one plate, resulting from electrode angle, causes undercut. Since the weld metal is fluid while being deposited, it will flow away from one plate, if the position of the work permits, and cause an undercut.

6. Flux pockets and inclusions are defects that occur when the material is not clean. Flux and oxides are either included in the weld metal or replace weld metal in some areas. Designs that have "closed angles" encourage flux pockets but they can be avoided by proper welding position. Too low welding heat prevents the flux from becoming fluid enough to float on the surface of the weld metal. Large misshapen tacks may trap flux if insufficient care is taken to prevent. When an electrode directs the arc ahead of the weld deposit flux entrapment is encouraged.

Fig. 6—Ryan Arc Welder Joins the Stainless Steel Sections of an Aircraft Exhaust Manifold in the Company's San Diego Plant

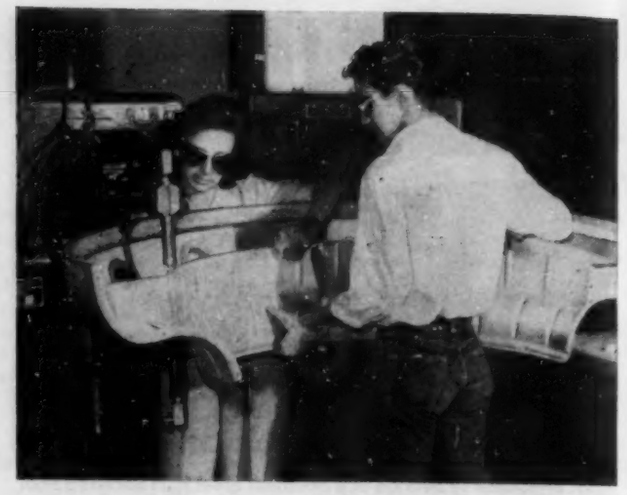

Fig. 7—Ryan Employees Spot Weld an Aircraft Diaphragm of Stainless Steel with Speed and Economy

7. Poor starts and endings on welds are common, especially on short welds 1 or 2 in. long. Characteristics are large deposits at the start and insufficient weld metal at the end. This defect is the result of carelessness usually and can be prevented by correcting the heat range, using a voltage control rheostat for starting and ending the weld, and properly positioning the work.

8. Excessive weld deposits result from several conditions or combinations of conditions: insufficient heat to fuse weld to parent metal, attempts to repair a "burned" hole or other defects, improper starting, large misshapen tack welds, failure to clean material, excessive weaving of electrode, and skipping back to cover an omission.

9. Shallow weld deposits, when insufficient weld metal is deposited, do not always produce an undercut but leave the weld with insufficient strength. If the heat range is high the rate of electrode travel must be fast enough to prevent excessive penetration, leaving insufficient weld metal. Too small diameter electrodes act similarly. These two factors must be coordinated.

10. The use of a standard proved weld procedure can not be overemphasized if uniform consistent welding is desired.

Gas-Welding Defects

The major uses of oxyacetylene welding at Ryan Aeronautical Co. are "gas tacking" and fusion welding of flanged seam type joints. Defects that are described are based on these applications. A combination of conditions may cause defects. Four key points are uniformity in height of flange, width of weld, speed, and amount of filler rod. Gas-welding defects are classified into 10 general groups.

1. Excessive penetration is usually caused by too high a flange or addition of filler rod to a flange of proper height. Excessive heat input requiring filler rod to bring

Fig. 8—Rough Appearing Seam Caused by the Tack Welds Which Preceded the Seam Welding. The Tack Welds Were Made Too Large and the Seam Welding Metal Spread Over Them to Give This Poor Appearance

weld height to proper level also contributes to this defect. Too slow welding speed, excessive weld width, and striving to produce a "flat" bead on the weld surface are also causes.

2. Insufficient penetration, characterized by little or nor einforcing bead or the underside of the weld, is usually caused by low heat input, too great weld height, too fast weld speed, improperly applied flux, torch at too low an angle or improper weld motion, and dirty scaly metal.

3. Undercuts are caused by too high heat input, too slow welding speed, insufficient flange or filler rod, too wide weld and poor welding technique. This defect parallels excessive penetration since they are caused by the same conditions.

4. Porosity makes a weld weak and brittle. Some 18–8 steels, particularly those stabilized by titanium, are susceptible. A smaller flame and tip and slower rate of travel are advantageous. Excessive puddling induces porosity. Mild steels are usually free from this defect.

5. Cracks may be caused by stresses set up by welding or by cold work and forming after welding. Since oxyacetylene welding affects a larger area than arc or atomic hydrogen welding because it is slower, thermal stresses are greater. Parts held rigid by jigs and fixtures are more likely to crack upon cooling. Postheating in the area surrounding tack welds prevents cracking. Stabilized 18–8 steels are not as prone to crack as high alloy steels of the X4130 and 4140 groups. Insistence that parts be correctly and accurately fitted before welding will reduce the amount of cold working required, thus decreasing the number of cracks produced.

6. Inclusions are not as common in oxyacetylene welding as in arc welding. Dirty, scaly parts, the presence of oxidized material in the flame and on the weld rod, fluxed welding rod and flux leaks into poorly fitted parts all produce this defect.

7. Excessive weld width results only from poor welding technique and poorly fitted parts.

8. Inconsistency, a defect characterized by a varied height and width of weld, usually results from poorly fitted parts, incorrect rate of welding, unevenly trimmed flanges, improperly positioned parts, part contour not properly aligned and poorly tacked parts.

9. Poor starts and endings are usually characterized by the burning away of parent metal on endings and large blobs of weld metal at the start and are usually the result of inexperience or use of incorrect weld procedure.

10. "Mushroom" penetration, where weld metal fails to bond at the edges, is not common because its usual cause is an unsuitable welding flux.

Atomic Hydrogen Welding Defects

In general, atomic hydrogen welds have the same defects as oxyacetylene welds, and for the same reasons. Since heat concentration is greater, the operator must pay closer attention and some faults in techniques are more noticeable in this process. The rate of welding is faster than gas welding and errors can occur faster.

In addition to the normal defects noted in gas welding, a defect known as "worm holing" may occur. This is caused by trapping of gases in the weld metal and can be prevented by reducing heat input and a slower rate of welding.

Spot-Welding Defects

Defects are allowed by most spot-welding specifications but are limited to 5% for structural and 10% for nonstructural spot welds. Since not all defects can be found by visual inspection, other means are employed. Four general groups of causes are improper spot-welder setup, improper surface preparation, poorly fitted parts and operator carelessness. Defects are of 16 types.

1. Excessive indentation indicates too small electrode diameter or tip radius, excessive pressure or heat, or a combination of these factors with poorly cleaned surfaces and poorly fitted parts.

2. Irregular-shaped spots indicate improper alignment and contour of tips, unsatisfactory surface preparation or poorly fitted parts.

3. Cracked or "burnt" spots indicate excessive heat or current dwell, excessive penetration, poorly cleaned surfaces, unsuitable electrode diameter or tip radius, excessive surface resistance caused by other than surface preparation, poorly fitted parts, internal or external splash, which are defined in 6 or 7, or incorrect pressure.

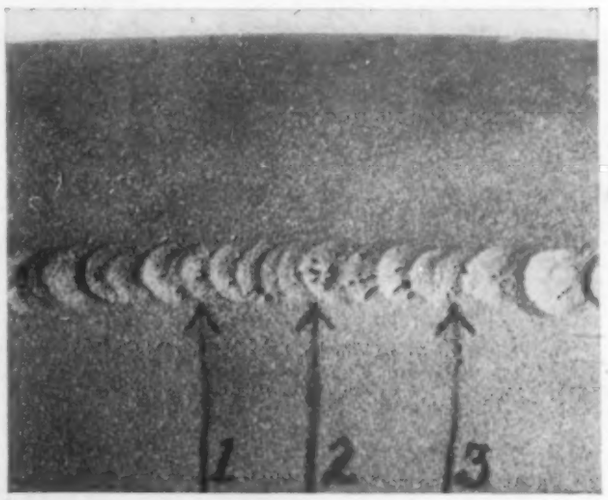

Fig. 9—Example of Porosity in Gas Flame Seam Weld Caused by Poor Technique

Fig. 10—Row of Poorly Placed Spot Welds. Due to Lack of Edge Distance, This Member Would Fall Far Below Required Strength Specifications

4. Spot welds too close to edge may result from lack of edge distance or operator carelessness.

5. Low shear strength, barring defective welds, results from insufficient cross-sectional weld area. This indicates either low penetration (less than 20% of sheet thickness) or merely too small diameter weld, which can be corrected by adjustment of machine variables. In rare instances insufficient pressure may be the cause. Inconsistent shear strength creates a condition where weakening and failure of weaker spot welds throw overloads on adjacent spot welds, thus causing progressive failures.

6. Surface or external splash is displaced or extruded parent metal, which weakens the spot weld. A number of conditions or combinations of incorrect conditions cause overheating, which makes the metal plastic through its entire thickness.

7. Internal splash occurs at the bond as a result of a number of preventable and incorrect conditions that prevent the normal retention of weld metal in the area to be bonded.

8. Excessive penetration (more than 80% of sheet thickness) weakens joints by reason of low tensile strength and rapid failure under vibration and fatigue in shear loading. Extreme stress concentration is caused around the weld spot. Excessive heat or weld time are the usual causes. Localization of heat by too small electrode tip may be the cause.

9. Excessive sheet separation is usually encountered in poorly fitted parts. The spot weld becomes a column joining the sheets. Pressure should be held long enough for the plastic metal to freeze. Adequately cooled electrodes aid in cooling the plastic metal.

10. Insufficient penetration is indicated by too low shear strength. Spot welds of correct diameter and shape usually have enough shear strength if penetration exceeds 20% of sheet thickness. Increase in heat range or weld time or both is the solution.

11. Internal cracks, either parallel or perpendicular to the sheet, may be caused by too large electrode diameter, which produces a large cast structure and causes stains on cooling. Too short a hold time may release stresses before the plastic metal is strong enough to resist them.

12. Porosity is usually found near the center of the cast area of the spot weld and is indicative of poor welding technique. It can be corrected by proper surface preparation, machine settings, pressure, heat range and weld time.

13. Weld inclusions are associated with poor surface preparation or lack of cleanliness.

14. Surface inclusions are also associated with poor surface preparation and dirty, misaligned and overheated electrodes. Excessive pressure may also contribute to this defect.

15. Incorrect spacing must be guarded against. The pattern of spot welds should be designed to give certain joint efficiencies. If this pattern spacing is not maintained, joint strength is reduced. Care in maintaining proper spacing, as given by design, cannot be overemphasized.

16. Poor fit of parts results in spot welds being left in tension, thus having from 0 to 25% of required shear strength. Good design for spot welds demands that a tension loading is never permitted. Poor fits may also cause excessive sheet separation, internal splash, excessive indentation, distortion of the completed unit, inconsistent welds and poor appearance.

Familiarity with welding defects and their causes can be used to advantage on the drafting board where parts can be designed to minimize some of the factors that are likely to cause difficulty in welding. Designers can indicate by dimensioning or notes the various requirements respecting welding quality, cleaning of surfaces, use of jigs or fixtures, penetration limits, spacing of spot welds or other conditions.

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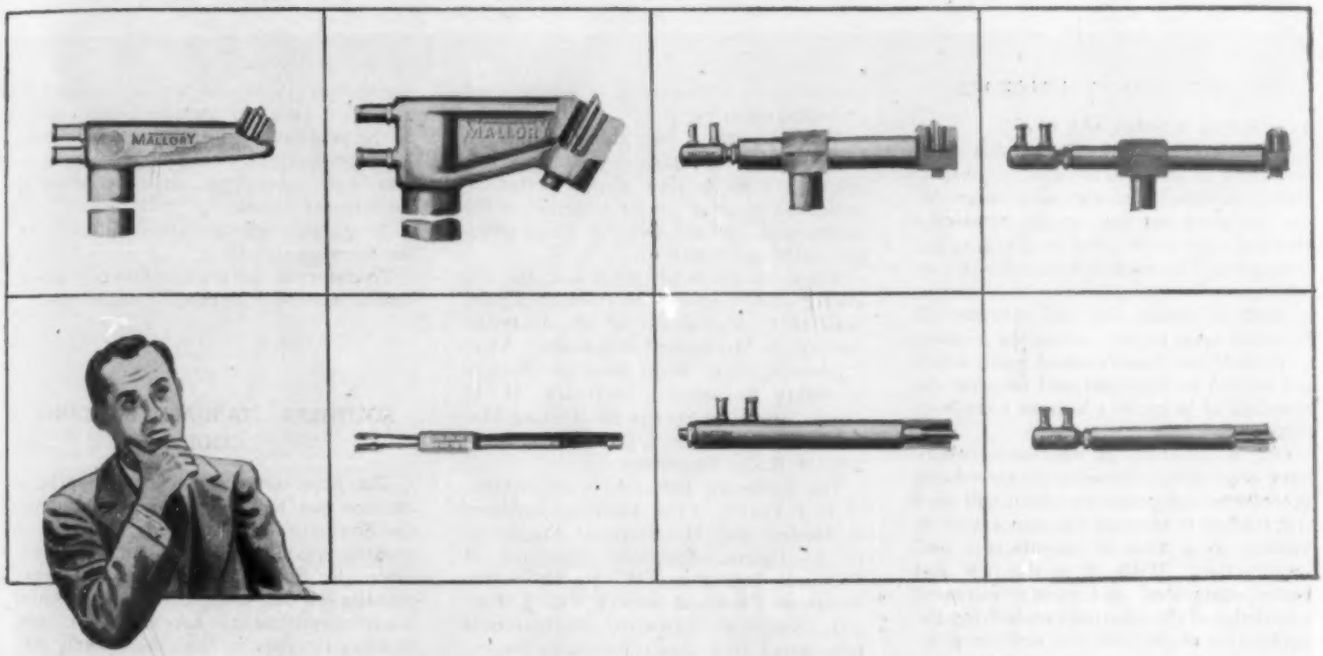

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ACTIVITIES – RELATED EVENTS

MESSAGE FROM OUR PRESIDENT

Dear Fellow Member of A.W.S.:

As the wheels of war industry slow down and many of our members seek new opportunities in other lines of activity than welding, we must not look at the downward trend in our membership as anything but temporary. As we look forward with confidence to the inevitable surge of peacetime activity we realize that our industry will be called upon in ever-increasing measure to provide the manufactured goods which are needed to maintain and increase the standard of living to which we have been accustomed.

Out of the stress of wartime necessity have come new improvements in welding procedures and processes which will tend still further to increase the importance of welding as a tool of manufacture and construction. With all of the new and better equipment, and greatly increased knowledge of the principles underlying the application of the different welding processes, our opportunity as an industry for the future is excellent. If each and everyone of us members of the A.W.S. will do his part in spreading newer knowledge of welding among all those concerned with the fabrication of metal structures, we shall certainly create an interest in the service which our SOCIETY can perform. This will inevitably lead to an even greater and more substantial membership than that which was created by the necessity of our nation's recent war effort.

Yours for Greater A.W.S.

WENDELL F. HESS, *President*

A.W.S. BY-LAW AMENDMENTS

By-Law amendments submitted with letter ballot to the membership for vote under date of April 26, 1946, now stand approved and will be incorporated in the By-Laws appearing in the 1947 Year Book.

ENGINEERING SOCIETIES COUNCIL OF NEW YORK ORGANIZED TO COORDINATE PROGRAM OF LOCAL CHAPTERS OF ENGINEERING SOCIETIES

Announcement was made recently at the Engineering Societies Building, 29 W. 39th St., of the organization of the Engineering Societies Council of New York, comprising delegates representing the local chapters of engineering, scientific and technical societies.

The purpose of the new organization is to enable the engineering profession to render in Greater New York a better coordinated program in the interests of the public and the members of the participating organizations.

The announcement stated that the following officers have been elected: Chairman, H. C. R. Carlson, of The American Society of Mechanical Engineers; Vice-Chairman, H. P. Wall, American Society of Safety Engineers; Secretary, M. P. Davis, American Society for Testing Materials; and Treasurer, H. F. Dart, Institute of Radio Engineers.

The following Directors were elected: O. B. J. Fraser, of the American Institute of Mining and Metallurgical Engineers; E. J. Lyons, American Institute of Chemical Engineers; W. F. O'Connor, American Chemical Society; C. S. Purnell, American Institute of Electrical Engineers; H. J. Ryan, American Society of Heating and Ventilating Engineers; and E. M. Sherwood, American Society for Metals.

The local chapters of the following Societies are represented: American Institute of Chemical Engineers, American Institute of Electrical Engineers, American Institute of Mining and Metallurgical Engineers, American Society of Heating and Ventilating Engineers, American Society of Mechanical Engineers, American Society for Metals, American Society of Safety Engineers, American Society for Testing Materials, American Society of Tool Engineers, American Chemical Society, AMERICAN WELDING SOCIETY, Illuminating Engineering Society, Institute of Radio Engineers and the Society of Motion Picture Engineers.

The purposes of the new Council as outlined in detail in the constitution which has been adopted are as follows:

To provide a medium for cooperative action by the member societies on matters of mutual interest which are beyond the scope of the individual organization or which can be performed better by cooperative action.

To encourage interest and participation in public affairs which are scientific or technical in scope.

To cultivate greater appreciation by the public of the part which engineering, science and technology contribute to human welfare.

To provide a means of more effective public service by the member societies of the Council.

To promote greater unification of the engineering profession and cooperate in a general program for the enhancement of the professional status of the engineer.

To promote coordination and integration of the inter-organization activities of the member societies.

To publish information of interest to the member societies.

To cooperate with organizations having similar objectives in other communities.

SOUTHERN STANDARD BUILDING CODE

The first code designed for Southern construction has just been published by the Southern Building Code Congress, a growing organization of 62 southern cities. Since the South has building problems peculiar to its own section, and since many requirements necessary for safe building in other sections are entirely different in the Southland, it is believed that this code will serve the purpose of preventing penalties on builders in that section.

Among the problems faced by southern builders, and not by other builders, is the handling of large quantities of natural gas, the heat and humidity of that section, the varying wind pressures and the lack of heavy snows and earthquakes. The new code, taking these things into consideration, has been written so that the southern builder will be neither penalized for those things which are not prevalent in his section, nor will the safety of the citizens be neglected due to standards set up for entirely different conditions.

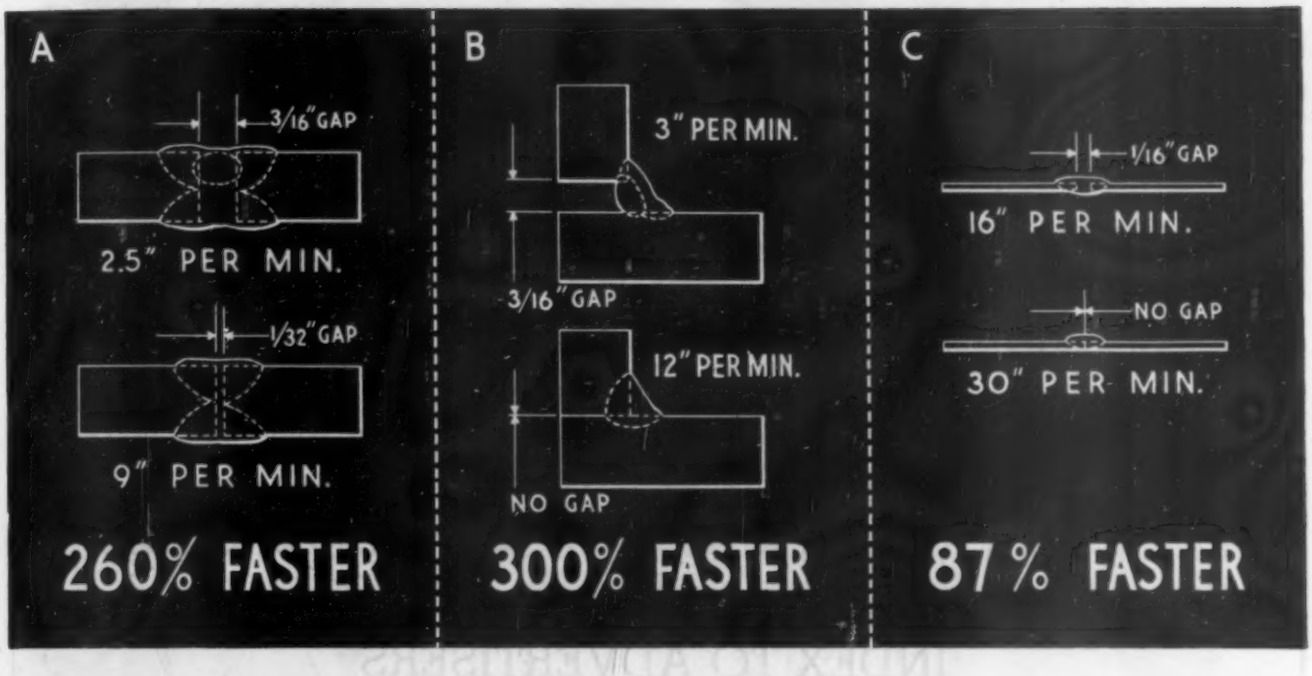
The code makes adequate provision for the use of welding, through incorporation of a large part of the material contained in the AMERICAN WELDING SOCIETY'S Code for Arc and Gas Welding in Building Construction, 1941 edition.

This is the first code ever written exclusively for the South, and while the sponsors do not claim that it is a perfect code, a research organization has been set up whereby inequalities can be ironed out and innovations can be evaluated.

This organization works through committees of engineers, architects and building officials in its member cities who meet periodically to discuss the provisions of the code and methods of keeping the code abreast of the times. The organization will hold its next meeting in New Orleans, November 12 to 15, when the building officials will hold their annual convention for discussion of mutual problems, and

MR. STRACHEY: **Here's food for thought to help you get the full measure of competitive advantage from arc welding:**

GET GOOD FIT-UP



Care in cutting, forming and fitting up of plates and shapes to be welded pays big dividends. By improving fit-up of joints, you increase welding speed and thereby cut costs and minimize distortion.

EXAMPLE A—This square butt joint in 3/8" plate with gap of 3/16" is made at an arc speed of 2.5" per min. With recommended gap of 1/32", speed is 9" per min.... 260% faster.

EXAMPLE B—This fillet weld in 1/2" plate, with 3/16" gap, is made at an arc speed of 3" per min. With no gap, speed is 12" per min.... 300% faster. Both welds have a 5/16" throat.

EXAMPLE C—This butt joint in 14 ga. sheet, with 1/16" gap, is made at an arc speed of 16" per min. With no gap, speed is 30" per min.... 87% faster.

The sign of abundance. When you see 3 DOTS on an electrode, you know you have genuine "Fleetweld" ... the world's leader for *low cost, speed* and *quality*. "Fleetweld" incorporates the full measure of Lincoln's pioneering research and worldwide engineering experience.

Handy pocket manual, giving, "Fleet-Welding" procedures for all types of joints in mild steel, free on request. Ask for Bul. 444.

THE LINCOLN ELECTRIC COMPANY • DEPT. 56 • CLEVELAND 1, OHIO

America's greatest natural **recourse**

ARC WELDING

various committees will meet to work out changes and additions for the next edition of the code, which will appear in 1948.

NEW HEADQUARTERS FOR AMERICAN BUREAU OF SHIPPING

Mr. J. Lewis Luckenbach, President of the American Bureau of Shipping, has announced that the main offices of the Bureau will be moved to its new headquarters at 45 Broad St., New York City, on or about July 24th.

The building, purchased last year, is eight stories in height on a plot 64 ft. by 130 ft. and is of fireproof steel and concrete construction. It has been thoroughly modernized and air-conditioned throughout and alterations have been completed to fit the requirements of the Bureau.

Among the new features incorporated in the building is enlarged facilities for the testing of materials under modern methods.

The executive office will be on the sixth floor, on which floor the Board Room will also be located where the meetings of Managers, Members and other committees of the Bureau will be held for the conduct of the general business of the Bureau.

The New York Port Surveyors' Department, located on the second floor, will be provided with every facility to expedite the handling of the numerous ship surveys necessary in the greatest shipping center in the world. Here, also, are received daily many reports from the Bureau's surveyors stationed at shipyards, steel mills, engine building plants and ship-operating centers all over the country and abroad.

The Record Department and Accounting Department will be located on the first floor. The Record Department is responsible for compiling and publishing the Bureau's yearly "Record" and the 1946 issue is the 78th annual volume of this 2000-page ship register.

The American Bureau of Shipping during the five years of war activity handled approximately 7650 new vessels of over 40,100,000 gross tons and 56,500,000 deadweight tons, which were built to class and to the Rules of the Society. The Bureau has become for the first time, through the war, the largest classification society in the world, it having under classification about 900 vessels.

The American Bureau was founded in 1862 and is now in its 84th year of service to the American ship owner, shipbuilder, underwriter and Government.

A.S.M. OFFICERS

The American Society for Metals today announced five nominees for the Society's national officers and trustees for 1946–47. Such nominations are tantamount to election.

Arthur L. Boegehold, head of the metallurgy department, Research Laboratories, Division, General Motors Corp., Detroit, incumbent vice-president of the Society, was nominated for president. Mr. Boegehold is a graduate of Cornell University and has been with General Motors since 1925, prior to which he was with Remington Arms Co., and the Bridgeport Brass Co., both of Bridgeport, Conn. He is a past chairman of the Detroit Chapter of the Society and was selected to deliver the important Campbell Memorial Lecture before the A.S.M. in 1938.

Francis B. Foley, vice-presidential nominee, was graduated from Girard College and started his metallurgical career with the Midvale Co., Nicetown, Philadelphia, Pa., in 1905. Later he taught metallography at the University of Minnesota, engaged in research projects for the U. S. Bureau of Mines. In 1926 he returned to the Midvale Co. as superintendent of research. He is past chairman of the Philadelphia Chapter of the Society.

William H. Eisenman, national secretary of A.S.M. since its organization in 1918, was nominated for re-election for his 15th consecutive 2-year term.

Dr. John E. Dorn, associate professor of physical metallurgy of the University of California, and Dr. Arthur E. Focke, research metallurgist of the Diamond Chain and Manufacturing Co., Indianapolis, were nominated for two-year terms as trustees of the Society. Dr. Focke is past chairman of the Indianapolis Chapter of A.S.M.

Formal elections and induction into office will take place at the A.S.M. annual meeting in Atlantic City during the week of November 18th as part of the National Metal Congress and Exposition.

INDEX TO ADVERTISERS

Air Reduction Sales	Outside back cover
Aluminum Company of America	873
American Brass Company	883
American Chain & Cable Company, Inc.	895
American Optical Co.	871
Anti-Borax Compound Company	878
Arcos Corp.	Inside front cover
Bastian-Blessing Co.	872
Champion Rivet Company	875
Eastman Kodak Company	887
Eisler Engineering Co.	878
Electroloy Co., Inc.	882
Eutectic Welding Alloys Co.	879
Federal Machine & Welder Co.	903
General Electric Co.	877
General Electric X-Ray Corp.	881
Harnischfeger Corp.	890 and 891
Hobart Brothers Co.	795
International Nickel Co.	867
The Lincoln Electric Co.	868 and 869
The Linde Air Products Company	797
P. R. Mallory & Co., Inc.	865
Metal & Thermit Corporation	885
National Carbide Corporation	874
National Electric Welding Machines Co.	889
National Metal Congress and Exposition	906
New Mexico Steel Co.	880
Oakite Products, Inc.	880
Page Steel & Wire Division	895
Penn Tool & Machine Co.	899
The Reid-Avery Company	893
Resistance Welder Mfrs. Association	904
Revere Copper and Brass, Incorporated	897
Sciaky Bros. Inc.	880 and 905
Shawinigan Products Corp.	878
The Sight Feed Generator Company	876
Tube Turns	901
Union Carbide and Carbon Corp.	797
Victor Equipment Co.	798
Westinghouse Electric Corporation	Inside back cover

THIS MITTEN

New A-O COVER-MITTS

make mittens last longer

GOES INTO THIS MITT

The new A-O 6X152 Cover-Mitt is designed to fit over welders' full mittens or one-fingered mittens, substantially adding to their life. It is made from split horsehide leather, specially tanned to resist heat and withstand rough wear. Slips on easily.

May be ordered in pairs, or all "rights" or all "lefts." Your nearest A-O Safety Representative can supply you.

LIKE THIS

American Optical COMPANY *Safety Division*

SOUTHBRIDGE, MASSACHUSETTS
BRANCHES IN PRINCIPAL CITIES

LINCOLN FOUNDATION ISSUES BROCHURE ON $200,000 DESIGN-FOR-PROGRESS PROGRAM

A 48-page brochure containing rules and other pertinent information on The James F. Lincoln Arc Welding Foundation's $200,000 Design-for-Progress award program, has just been issued by the Foundation.

The booklet lists the 15 classifications and 43 divisions that have been established for participation and the 452 separate awards which range from the $10,000 main award to the 217 honorable mention awards of $100 each. It also contains a chart showing how these 452 awards will be distributed.

The highest award that will be made will total $13,200, the booklet states, which includes a $700 first divisional, $2500 first classificational and the $10,000 first main program awards.

The Design-for-Progress program, which closes June 1, 1947, is expected to bring a flood of papers from engineers, designers, architects, draftsmen, production and maintenance officials, researchers, educators, welding shop and garage owners and from workers in all phases of the vast arc-welding industry.

The rules and conditions of the program occupy 16 pages and describe in detail such items as subject matter to be considered, limitations of subject matter, eligibility, treatment of subject matter, suggestions to be considered before writing papers, the method by which papers will be judged and other information which participants should review before preparing their award papers.

As the Foundation brochure points out, its object and purpose is to encourage and stimulate scientific interest in, and scientific study, research and education for the development of the arc-welding industry through advance in the knowledge of the design and practical application of the arc-welding process.

"Just as the arc-welding process was significant in production for victory," it continues, "so is arc welding indispensable to peacetime industry.

"It is in recognition of the widely acknowledged benefits of this modern process and the fact that additional benefits still remain virtually untapped that The James F. Lincoln Arc Welding Foundation is sponsoring this $200,000 Design-for-Progress Award Program. Its objective is to encourage the study of welded design, research application and use of arc welding through the preparation and writing of papers."

The brochure points out that in addition to the stimulation of scientific research and design the Foundation also makes the results of these studies available generally through the publication of a number of books containing the outstanding papers submitted.

It lists the 15 classifications and 43 divisions that have been established for participation which include arc-welding development in the aircraft, automotive, container, furniture and fixture, functional machinery, industrial machinery, personal service machinery, railroad, building and bridge industries, in watercraft, welderies, commercial welding establishments, maintenance departments and research and educational categories.

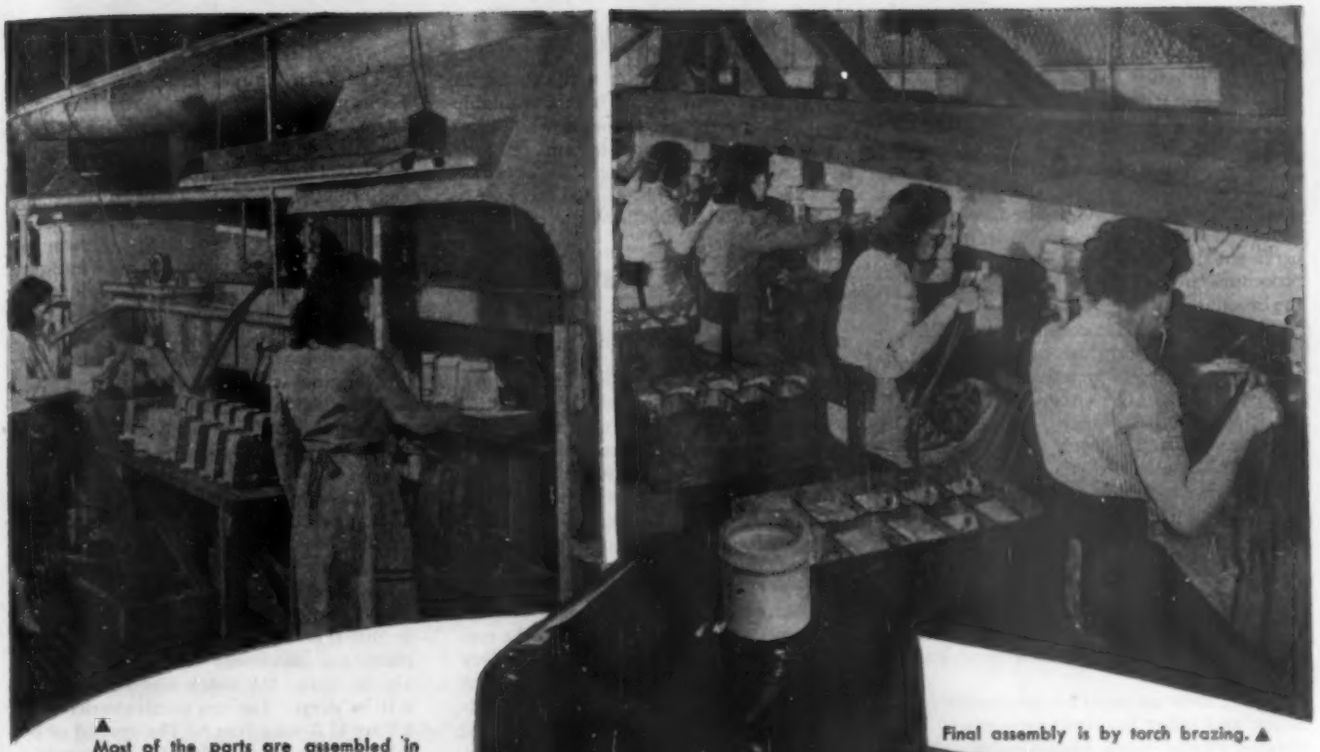
According to the table of awards, participants will receive one $10,000 award, one $7500 award, one $5000, fifteen of $2500 each, fifteen of $1500 each, fifteen of $1000 each and fifteen of $800 each. There are also 43 awards of $700 each, 43 of $500 each and 43 of $150 each. The additional 217 honorable mention awards brings the total awards to 452 and the amount to be paid to $200,000.

The 172 divisional awards will be determined first and from them will be selected the 60 papers to receive the classificational awards. These, in turn, will be judged to determine the three main awards and after the divisional, classificational and main awards are determined, papers will be selected to receive the honorable mentions.

Under the listing of limitation of subject matter, the brochure discloses that participants, in order to qualify in the first eleven classifications, must describe an improvement made on a machine, structure or part that was either designed or redesigned and built or manufactured within the period from June 1, 1946 to June 1, 1947, or one that was not built for some reason which should be stated. The machine, structure or part may also be one that was first built between June 1, 1946 and June 1, 1947 from studies or designs made prior to that period.

Products or structures entirely or partially arc welded prior to June 1 of this

Outstanding Design for . . . Outstanding Performance!
RegO Standard Manifolds Combine Major Features to Give You Custom-Built Features
RegO offers a complete line of standard manifolds—wall-mounted and cross-type models in a range of sizes up to the largest for supplying complete pipe systems . . . and, in addition, there's a series of portable styles which provide manifold advantages at low cost and which fully meet the requirements for general use in the field.
Specify RegO Manifolds . . . you will be certain to get the full benefit of engineering know-how which has a background of many years of practical designing and manufacturing experience.
Send for catalog today!
RegO Manifolds for OXYGEN ACETYLENE HYDROGEN NITROGEN and other high pressure gases.
The BASTIAN-BLESSING Company
4201 N. Peterson Ave., Chicago 30, Ill.
Pioneer and Leader in the Design and Manufacture of Precision Equipment For Using and Controlling High Pressure Gases.
REGO



▲ Most of the parts are assembled in this tunnel-type brazing furnace.

Final assembly is by torch brazing. ▲

◀ This oil separator, made of Alcoa Aluminum Brazing Sheet, is assembled with the help of Alcoa Brazing Wire and Flux.

Put BRAZING on a production basis with Alcoa Aluminum

Tack-welded to hold its eight parts in place, a single trip through the tunnel brazing furnace completes their assembly. The inspector approves it, and girls add the cover by torch brazing. A black Alumilite* finish readies it for service.

Vital part of this oil separator is the V-Shaped screen made of 0.032″ Alcoa Aluminum Brazing Sheet; 225-0.033″ holes per square inch. The brazing techniques employed keep those perforations open and clean, and result in a pressure-tight unit.

What's your aluminum assembly problem? Alcoa engineers will gladly assist in solving them. Call the nearby Alcoa office, or write ALUMINUM COMPANY OF AMERICA, 1933 Gulf Building, Pittsburgh 19, Pennsylvania.

Process patented by Aluminum Company of America

ALCOA FIRST IN ALUMINUM

IN EVERY COMMERCIAL FORM

year, will be eligible provided further progress and improvement is made in design, manufacture or construction within the specified period. In such cases, the papers should only cover the improvement made.

Complete instructions for classifying papers, details of presentation of subject matter, factors in judging papers, procedure of the Jury of Award and other pertinent details governing the program's procedure are contained in one section of the brochure.

There are 24 pages containing 86 illustrations and factual data offering typical examples of subject matter for study in connection with the program, to assist participants in determining the scope and treatment of their entrees. A full page index is also included to facilitate and catalog the brochure's vast content of clarifying information.

Each set of photographs and descriptive material appears under a separate classification, according to alphabetical listing of industries, offering participants an opportunity to study other arc-welding advancements previously described during past award programs.

Among those pictured are illustrations of design and other improvements made on airplane engine parts, tip assemblies, airplane boilers, and tubular fuselages. Under the automotive classification there are pictures of improvements on Diesel-powered tractor-scrapers, fire trucks, tank trailer units, wheel assemblies, and each industry eligible in the competition is included in this helpful and instructive section of the booklet.

The brochure is clear and concise in every respect and should be of invaluable aid to prospective participants who desire to take part in this popular and progressive award program. It can be obtained by writing to The James F. Lincoln Arc Welding Foundation, Cleveland 1, Ohio.

MATERIALS FOR SAFETY WEARING APPAREL

Commercial Standard CS129-46

Purpose: The purpose of this commercial standard is to (*a*) provide protection to the wearer of safety wearing apparel through the establishment of standard minimum quality requirements of such apparel; (*b*) serve as a basis for fair competition between manufacturers; and (*c*) provide a foundation for guaranteeing the quality of the materials used in the manufacture of this product.

Scope: This commercial standard covers minimum quality requirements for the material used in the manufacture of safety wearing apparel, including: (*a*) asbestos fabrics; (*b*) cotton fabrics, flame-resistant; (*c*) leather; (*d*) woolen fabrics; (*e*) accessory materials.

This standard also covers methods of test and methods of labeling to certify or guarantee quality.

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. Price, 5 cents.

SWISS BOILER SOCIETY

The 77th Annual Report of the Swiss Society of Boiler Owners states that 48 of the 93 boiler explosions reported in Switzerland during 1945 were caused by thinning of the plates by corrosion. The Society performed a series of tests to determine whether plates thinned by corrosion, excluding caustic embrittlement, can be safely built up to the original thickness by welding. The plates for test were initially $1^1/_2$ in. thick and were reduced about $^3/_8$ in. in thickness by corrosion. The corroded areas were cleaned and built up to the original thickness by an expert arc welder, the plates being in the vertical position. The following tests were made on specimens cut from the repaired plate.

(*a*) Tensile tests on rectangular bars, which averaged 29,500 psi. yield point, 53,000 psi. tensile strength, 51 to 56% reduction of area, and 17 to 18% elongation. The strength is equal to the original boiler plate but the elongation is a little lower.

(*b*) Notch impact tests with the notch in different locations in weld metal and plate, the specimens were $^3/_8$ in. square, $1^3/_4$ in. span; the notch was 0.08 in. wide, 0.10 in. deep. The test results varied from 4.7 to 13.3 mkg./cm.^{2} The spread of results was much wider than for the unwelded plate.

(*c*) Pulsating tension fatigue tests of bars having a cross section of $^1/_2$ sq. in. The stress varied during each cycle from nearly zero to maximum tension, applied 350 cycles per minute. The fatigue

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Carbide
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EFFICIENT
ECONOMICAL
DEPENDABLE

FOR WELDING and CUTTING
Use National Carbide in the Red Drum
Write us for information as to nearest available stock.
60 E. 42nd St. NATIONAL CARBIDE CORPORATION New York 17, N. Y.

For

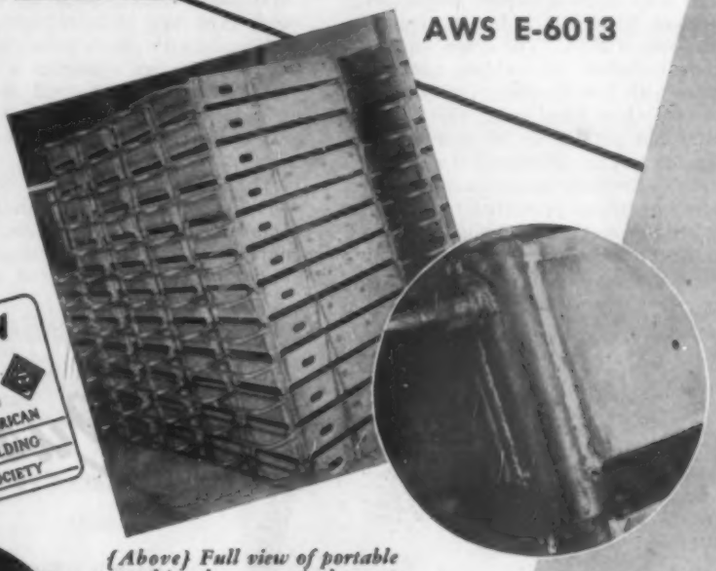
HIGHLY SATISFACTORY WELDS OF THIN GAUGE METAL USE *the* CHAMPION

NEW GRAYDAC ELECTRODE

AWS E-6013

EXCELLENTLY adapted to thin gauge metal, ***GRAYDAC*** Electrode provides just sufficient penetration to make a good bond which allows for grinding flush without weakening the weld. On vertical down the bead is flat and exceptionally smooth. Spatter is held to a minimum and slag easy to remove.

Competitive tests showed ***GRAYDAC*** superior in bead appearance, penetration, ease of starting, vertical performance and all 'round handling. ***GRAYDAC*** is especially recommended for use with the low input type of Transformer Welding Machine.



{Above} Full view of portable machine bases and close up view of corner weld made with **CHAMPION GRAYDAC Electrodes.**

{Above} Full view of bases for meat cutting machines and close up of corner weld made with **CHAMPION GRAYDAC Electrodes.**

APPLICATIONS

Auto Body Panels	Sheet Metal Work
Farm Equipment	Air Conditioning Equipment
Cans	Bus Bodies
Machine Parts	Fender Repairs

THE CHAMPION RIVET COMPANY

CLEVELAND, OHIO — **EAST CHICAGO, IND.**

strength of four specimens was 26,400 to 30,500 psi. These specimens contained a few blowholes. A fifth specimen without blowholes had a fatigue strength of 38,000 psi. On the whole, these results are slightly lower than for the original plate.

The Society considers that repairing thinned surfaces by welding is permissible under the following three conditions:

1. The plate must show no abnormal changes due to corrosion.
2. Welding must be done by a welder qualified for such work using heavily coated electrodes.
3. The welding must be inspected, if necessary by polishing and etching, X-ray or magnetic testing.

If the tinned area is of very large extent, it may be cut out and a patch inserted. The corners of the patch must be rounded to a generous radius. The welding sequence must be such as to minimize shrinkage stresses.

SWISS ACETYLENE SOCIETY

The 35th Annual Report of the Swiss Acetylene Society records 1022 members at the end of 1945. The activities of the Society included: 25 welding instruction courses with 309 students; sales of 2000 copies of their handbook, *The Practical Welder* and publication of their monthly magazine. The Technical Information Bureau of the Society continued to answer welding questions presented to it by the membership, and gave welding demonstrations at the Swiss Fair. The usual testing of carbide, acetylene, oxygen, welding rods, etc., was carried out as well as physical and X-ray tests of welded joints. A new and extensive series of tests on gas welds was begun and will be reported upon completion. The annual report lists the routine inspection of acetylene installations by the Society's inspectors, both for welding and for automobiles. Some revision was made during the year in the standards for calcium carbide and acetylene. Technical Committee No. 20 on Welding discussed the question whether gas-welded joints should be torch normalized to attain maximum notch impact value. Final action on this question is expected soon. The new president replacing Dr. Gandillon is Dr. P. Schläpfer, director of the Federal Materials Testing Laboratory in Zurich. The Society looks forward to renewed contact with welding societies in other countries now that the war is over.

FRENCH-ENGLISH DICTIONARY

English-French and French-English Technical Dictionary, by Francis Cusset, is an up-to-date and accurate technical dictionary which should be welcome to workers of every technical field.

Keeping up with the newest accomplishments in foreign countries is a vital requirement of all industrial and scientific research. This literary search is the first step toward new developments and inventions.

This handy volume was compiled to help the technical man in reading French technical texts. Translators, librarians and students will find it equally useful. The English equivalents of French expressions, and vice versa, were chosen with great competence and accuracy.

Here is a dictionary which covers many fields well. It should be in every technical library. Price $5.00. Published by Chemical Publishing Co., Inc., Brooklyn 2, N. Y.

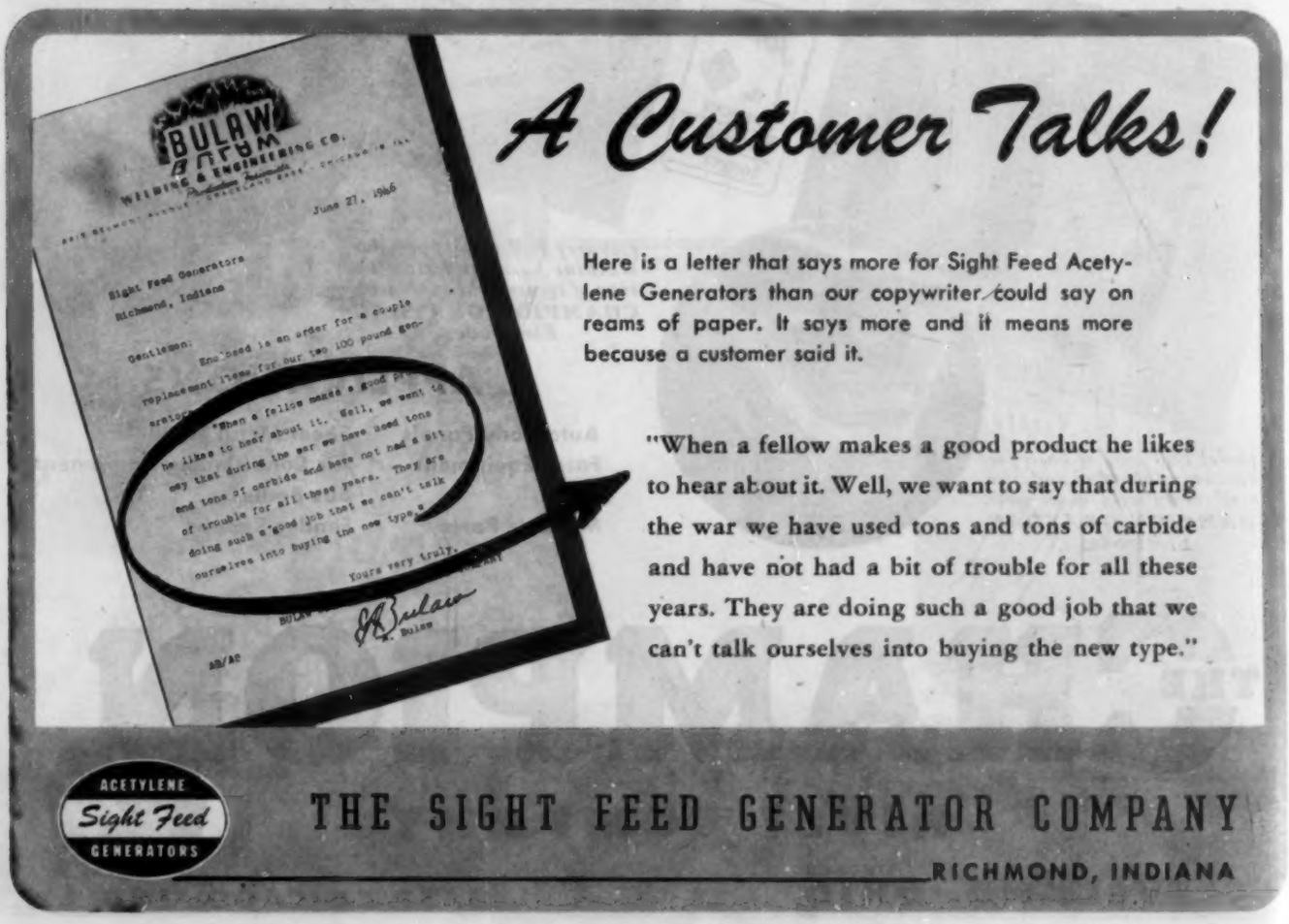
BUYING GUIDE

Designed to be of genuine help to the processor in all fields is a new bulletin, "Buying Guide of Allis-Chalmers Equipment for the Process Industries," just released by the Allis-Chalmers Mfg. Co., Milwaukee, Wis.

The 16-page booklet, generously illustrated, features a series of thumbnail "buying guides" aimed at helping the reader in making preliminary selection of any of a complete range of industrial products including motors, motor controls, power generation and distribution equipment, vibrating screens, feeders, washing equipment, pumps, crushers, grinding and roller mills, pyro-processing machinery, blowers and compressors V-belt drives, electronic heating and welding equipment.

Leading off with suggestions of primary decisions which must be made by the prospect in narrowing down the problem, each "buying guide" describes how Allis-Chalmers is prepared to aid in the proper selection of equipment through the wide range it offers.

The booklet, 25B6177B, is available on request from the Allis-Chalmers Mfg. Co., Milwaukee 1, Wis.


A Customer Talks!
Here is a letter that says more for Sight Feed Acetylene Generators than our copywriter could say on reams of paper. It says more and it means more because a customer said it.
"When a fellow makes a good product he likes to hear about it. Well, we want to say that during the war we have used tons and tons of carbide and have not had a bit of trouble for all these years. They are doing such a good job that we can't talk ourselves into buying the new type."
ACETYLENE Sight Feed GENERATORS
THE SIGHT FEED GENERATOR COMPANY
RICHMOND, INDIANA

UNIFORM WELDS... *Automatically!*

● The operator of this traveling resistance-welder at the Pullman Standard Car Manufacturing Co., gets consistent welds automatically

Equipped with a G-E electronic current regulator and synchronous control, this resistance welding machine travels the length of the Pullman car producing uniform welds automatically. Each of these welds is of equal strength because the current regulator *automatically compensates for varying line voltage and secondary circuit impedance.*

In welding these cars, two spot welds are made at a time, the spacing between the two varying in accordance with the dimensions of the parts and the strength specifications. As the spacing varies, the length of the secondary circuit changes, and in turn the current is changed.

Where formerly this shift meant frequent readjustments by the operator, guided by an extensive table of machine settings, now just one of two settings is needed, depending on whether the machine is welding Cor-Ten or stainless steel; the current regulator does the rest.

This regulator holds current within plus or minus 2 per-cent of normal, whereas, the unregulated current might vary as much as plus or minus 20 per-cent.

Even when space is uniform, current is affected by varying amount of magnetic material in current loop.

IMPROVES QUALITY

In this, and other applications such as welding propeller blades, metal barrels, etc., this regulator provides uniform quality welds when more or less metal is introduced in the welder throat.

FLEXIBLE OPERATION

The same settings can be used when operating a press-type spot welder, a gun welder connected to the same transformer, or when welding magnetic materials with a press-or gun-type welder.

—The current regulator is specially designed for use with G-E electronic resistance welding controls which include heat control by the phase-shift method.

For additional information ask our nearest local office for Bulletin GEA-4220. *Apparatus Department, General Electric Company, Schenectady 5, N.Y.*

GENERAL ELECTRIC

MALLORY EXPANDS

Establishment of a new plant at 8605 Livernois Ave., Detroit, Mich., is announced by P. R. Mallory & Co., Inc., Indianapolis, Ind. The new branch factory is now in operation manufacturing special resistance welding dies, electrodes and allied welding parts fabricated from Mallory alloys.

Extension of Mallory manufacturing activities to Detroit has been undertaken to provide immediate and emergency service to the automotive and metal working industries in the area, for which the Mallory Co. is an important supplier of welding, metallurgical and other products. Skilled workmen trained at the main Indianapolis plant and accustomed to handling the special Mallory alloys and processes are employed in the new Detroit branch to turn out the high quality products for which Mallory is known. The services of metallurgical and welding engineers from the Indianapolis office are on call to assist in any problems which require extraordinary attention.

The plant comprises 6400 sq. ft. of floor space and houses Mallory manufacturing and sales departments serving the Detroit area. The staff is headed by A. O. Braun, District Manager, and O. V. (Jack) Miller, Assistant District Manager. Bruce Chatterton, George F. Conway and Earl R. Sayre also will contact and lend assistance to users of welding equipment.

RESISTANCE WELDING LITERATURE

The Taylor-Winfield Corp. has just issued two important technical bulletins.

Bulletin 5-003 deals with portable welders, air operated. The different types of welders are described; valuable information given in regard to the selection of portable welding equipment and important welding data.

Bulletin 2-413 deals with production welders. This bulletin is designed to assist in the selection of proper resistance welding equipment for specific production jobs. Illustrations, photographs, charts, engineering data and descriptions are included.

Copies may be obtained on request of The Taylor-Winfield Corp., Warren, Ohio.

BOOKLET LISTS ARTICLES ON SPECTROGRAPHY

A 16-page bibliography of articles and books on spectrography has been released by the Eastman Kodak Co. The booklet lists articles and books covering the broader aspects of chemical spectrography, equipment and supplies, flash spectrography, infrared spectrography, mass spectrography, radiation sources, Raman Effect spectrography and ultraviolet spectrography. It may be obtained without charge from the Industrial Photographic Sales Division, Eastman Kodak Co., 343 State St., Rochester 4, N. Y.

FLOATING DRY DOCK LAUNCHED

The largest vessel ever to be launched on inland rivers slipped down specially built ways at Dravo Corporation's Neville Island plant on the Ohio River at Pittsburgh, Pa., on Saturday, August 10. The vessel is ARD-33, a self-contained, open-ended floating dry dock, designed by the Bureau of Yards & Docks, U. S. Navy, for the Bureau of Ships.

Admiral Ben Moreell, organizer of the famous "Sea Bees" and now Federal Coal Mines Administrator in charge of operating 3300 Government-seized bituminous coal mines, delivered a short address just prior to the launching of the huge vessel. Admiral Moreell's wife christened the dry dock with the traditional bottle of champagne, as it slid into the river sideways. The sideways launching is unique for ships of this size.

The ARD-33 is 448 ft. long and 97 ft. wide. More than 97 miles of welding—385,000 ft.—went into the ship-lifting Leviathan. Height to top of wing-wall is 45 ft. It has a lifting capacity of 6000 tons, and its 73-ft. wide docking chamber will accommodate most of the Navy auxiliary or tender type ships.

The dock could not be submerged in the Ohio River since it went down about 39 ft. during test, so U. S. Army Engineers "dug a hole" in the river bottom, 500 ft. by 150 ft., and the dock was tested at that point.

Buy "Proven Fluxes" with Years of Guaranteed Satisfaction behind them

The Trade-Name is "ANTI-BORAX"

Ask for Them *Unequalled for Quality*

A Flux for every metal: Cast Iron Welding Flux No. 1; Brazing Flux No. 2; Braz-Cast Flux No. 4 for bronze-welding cast iron; "ABC" Aluminum Flux No. 8 for sheet Aluminum and all alloys of Aluminum; Stainless Steel Flux No. 9; Silver Solder Brazing Flux No. 10; No. 16 Silver Solder Paste Flux.

ANTI-BORAX COMPOUND COMPANY

Fort Wayne, Indiana

Time Counts—
Gas cut and Weld with

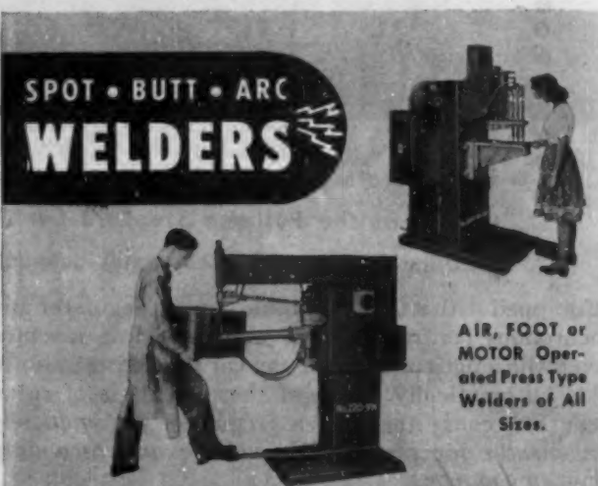
Shawinigan Carbide

SHAWINIGAN

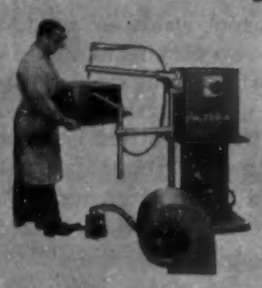
Join The American Welding Society

SHAWINIGAN PRODUCTS CORPORATION
EMPIRE STATE BUILDING, NEW YORK 1, N.Y.

SPOT • BUTT • ARC
WELDERS



AIR, FOOT or MOTOR Operated Press Type Welders of All Sizes.



We manufacture a complete line of resistance spot welders from ¼ to 300 KVA for all types of welding. There is an EISLER WELDER for every purpose.

Transformers of all types.

We invite contract spot welding in large or small quantities.

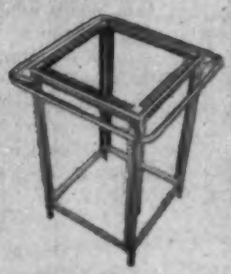
Write for Catalog

Chas. Eisler

EISLER ENGINEERING CO.

779 So. 13th St. (near Avon Ave.) Newark 3, N. J.

USE EUTECTIC *Low Temperature* WELDING RODS*



Steel table entirely welded without distortion completely eliminating costly finishing, using EutecRod 16.

THIS WELDING JOB ONLY POSSIBLE WITH EUTECTIC

Handle welded to aluminum pan with EutecRod 190. This alloy flows on aluminum like silver solder on brass—no after machining required.

THIS WELDING JOB ONLY POSSIBLE WITH EUTECTIC

Worn armature shaft overlaid with Bronzo-Chrome 185 at 1000°F without burning the insulation or distorting the shaft. Weld is highly wear resistant, but easily machineable.

THIS WELDING JOB ONLY POSSIBLE WITH EUTECTIC

Cracked cast iron cylinder head sealed with EutecRod 15, which is applied at the amazing low heat of 354°–600°F.

THIS WELDING JOB ONLY POSSIBLE WITH EUTECTIC

AVOID THESE WELDING DEFECTS caused by HIGH HEAT!

Distortion and Buckling

Stresses and Cracks

Brittle, therefore Poor Strength

Poor Machinability

Enthusiastic users call it the greatest advance in welding since the invention of the welding torch, as for the first time it is possible to obtain "true welds" without all the disadvantages of high heat.

You can save time and money on jobs and improve the quality of your work with EUTECTIC *Low Temperature* WELDING RODS and FLUXES*. You'll get strong, structurally sound, neat appearing welds that require less machining.

EUTECTIC *Low Temperature* WELDING RODS* are a new type of welding alloys which—1. *Give a true weld without fusion.* 2. *Bond to base metals well below the melting point of the base metal.* 3. *Form exceedingly strong welds through surface alloying.* 4. *Give faster, better welds at low cost.*

LET EUTECTIC *Low Temperature* WELDING RODS* SOLVE YOUR WELDING PROBLEMS. MAIL THE COUPON OR WRITE ON YOUR COMPANY LETTERHEAD FOR FULL INFORMATION.

Castolin Eutectic

EUTECTIC WELDING ALLOYS CORPORATION

ORIGINATOR OF *Low Temperature* WELDING ALLOYS*

40 WORTH STREET NEW YORK 13, N. Y.

140 Field Engineers in all principal cities of the United States and Canada to serve YOU.

*Trade Mark Reg. U.S. Pat. Off.

Please send me facts on EUTECTIC *Low Temperature* WELDING RODS and Fluxes,* and complete information on how to purchase a trial selection of 9 EutecRods for everyday use. Dept. WJ 9

Name..... Position.....

Company.....

Address.....

Admiral Moreell received his rank on June 11, 1946, becoming the first staff officer in the Navy to attain four-star admiralship. He is the first full Admiral who did not graduate from Annapolis since the naval academy was founded.

Aides to Mrs. Moreell during the launching ceremonies were Mrs. Jane T. Reside, Silver Spring, Md., and Mrs. R. J. Carballeira, Flushing, N.Y.

MUREX ELECTRODES

Applications, characteristics, physical and chemical properties, and recommended welding procedures for over 40 Murex Arc Welding Electrodes are illustrated and described in a 4-color, 92-page catalog recently issued by the Metal & Thermit Corp., New York, N. Y.

Broken down into use classifications, the new issue includes electrodes for a.-c. and d.-c. welding of mild steels, low alloy steels, bronzes and cast iron, as well as for hard surfacing, automatic welding and underwater cutting and welding work. A new line of basic welding accessories has also been incorporated.

Among the more outstanding new electrodes listed are: Murex Type HTS for welding sulphur-bearing, high-carbon and other difficult-to-weld steels; a "Chrome-Moly" series of eight electrodes in which the chemical composition has been varied to provide tensile strengths ranging from 77,500 to 130,500 psi.; the "Gardex" series, for low-cost impact and abrasion-resistant overlays, and the Type CT tubular steel electrode, originally designed for underwater cutting, but which has been found useful for open-air cutting of both cast iron and nonferrous alloys.

A useful feature of the new Murex catalog is an Engineering Data section which presents in simplified, tabular form, information designed to assist the welding engineer or shop foreman in planning and estimating welding job costs. A chart of A.W.S. welding symbols and a table of A.S.T.M. steels along with electrode and preheating recommendations for each steel are included in this section.

To facilitate quick selection and identification of the Murex electrode types required, an indexed Electrode Guide prefaces the main body of the book.

Requests for copies should be addressed on company letterheads to Metal & Thermit Corp., 120 Broadway, New York 5, N. Y.

NEWBURN MADE DISTRICT MANAGER

Stephen H. Newburn has been appointed manager of Air Reduction's Detroit District according to an announcement made by H. F. Henriques, General Sales Manager. A Penn State graduate, Mr. Newburn joined Air Reduction in 1936 as a district representative in Pittsburgh. In 1944 he was made assistant sales manager at Cleveland and was promoted to manager in 1945. Mr. Newburn succeeded G. J. Dekker recently elected vice-president of The Ohio Chemical and Mfg. Co., an Air Reduction subsidiary. Mr. Newburn is a member of the AMERICAN WELDING SOCIETY.

"LOW-TEMPERATURE" WELDING ALLOYS

A special issue of "The Eutectic Welder," monthly house organ of the Eutectic Welding Alloys Corp., contains some unusual photographs showing applications of the company's products to wartime metal joining problems. From delicate aluminum to such machinery as heavy stamping equipment, both production and maintenance low-temperature welding are interestingly portrayed.

Those interested may secure a copy of this publication by writing to the Eutectic Welding Alloys Corp., 40 Worth St., New York 13, N. Y.

A. C. BROWN APPOINTED DISTRICT MANAGER

A. C. Brown, Jr., has been appointed manager of Air Reduction's Cleveland District according to a recent announcement by H. F. Henriques, General Sales Manager. Recently returned after five years in the Army where he rose from private to captain, Mr. Brown started with Air Reduction in 1935. Before entering service, he served as salesman, and later as branch manager at Grand Rapids, Michigan. He succeeds Stephen H. Newborn appointed Detroit district manager. Mr. Brown is a member of the AMERICAN WELDING SOCIETY.

SURPLUS

SCIAKY ALUMINUM SPOT WELDERS

They are thoroughly factory-reconditioned, installed, serviced and "new-machine" guaranteed by the original maker.

They are offered at a savings of nearly one half. Welders formerly $9,100 to $10,160 are priced at $5,500 to $6,000, complete with rectifier . . . some with built-in rectifiers.

The machines are rated 50 KW and operate on the exclusive Sciaky Electromagnetic "Stored Energy" principle with patented "Variable Pressure Cycle." Capacity on aluminum and other light alloys: .016" plus .016" up to and including .080" plus .080". Speed on two thicknesses of .040" is 90 spots per minute. Throat depth is 36".

The quantity is limited. You are urged to act at once. Write, phone or wire for details.

SCIAKY BROS. Inc.
4915 W. 67th St. Chicago 38, Ill.

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Mounted in Knurled
BRASS *Handled*

LARGE STOCK
PROMPT DELIVERY
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Box 691, Albuquerque, N. M.

. . . is THIS your cleaning problem?

Removing Brazing Flux From Alclad Before Anodizing?

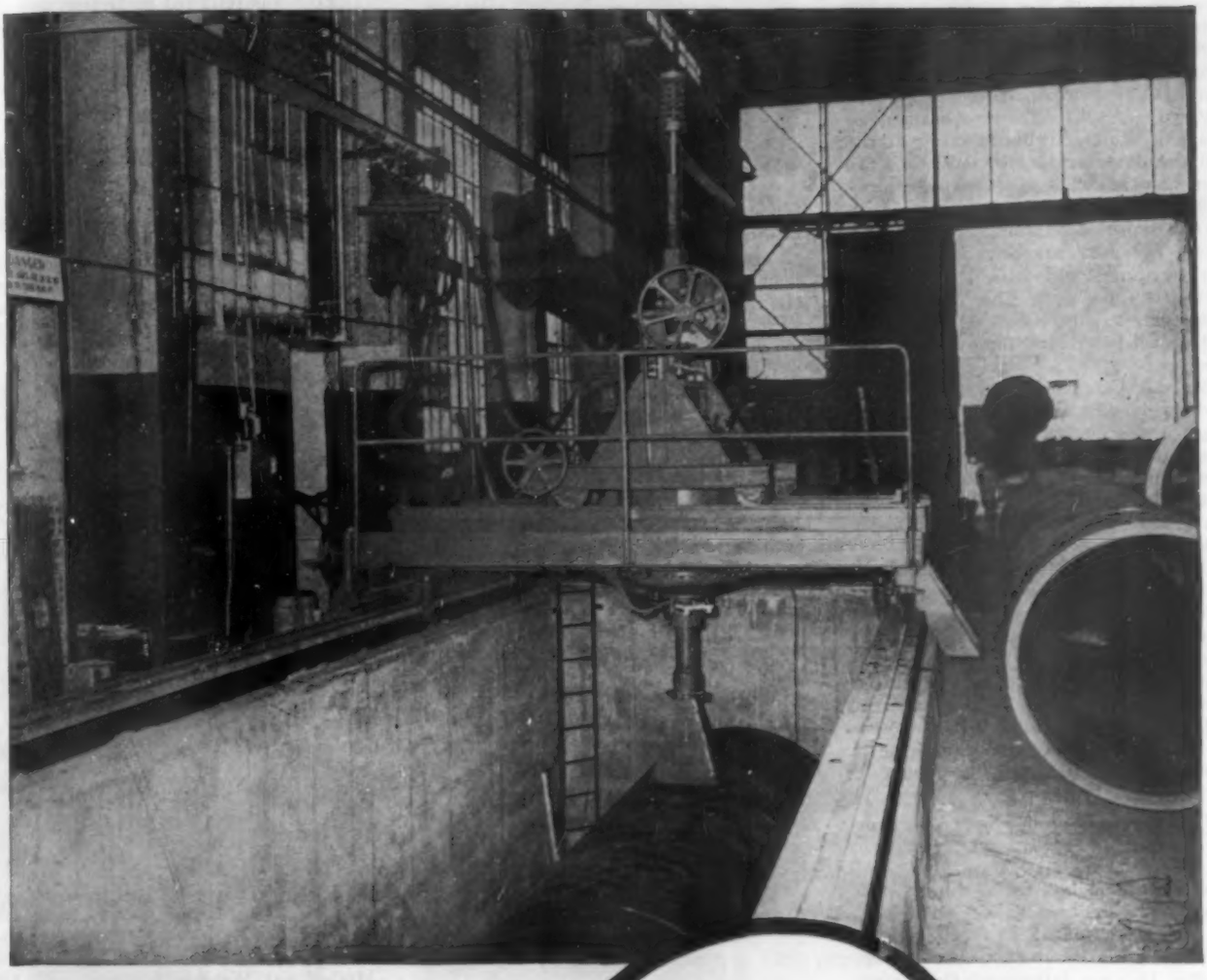
If you are having difficulty in removing brazing flux from Alclad parts prior to anodizing and painting . . . if your present technique or material is taking too long to do the job, try the fast, successful Oakite method of handling this important work.

You will find, as have many others, that the Oakite technique removes accumulations easily and provides excellent results. Your nearby Technical Service Representative will gladly give you complete details—without obligation. Write today.

OAKITE PRODUCTS, INC., 18E Thames St., NEW YORK 6, N. Y.
Technical Service Representatives Conveniently Located in All Principal Cities of the United States and Canada

OAKITE *Specialized* **CLEANING**
MATERIALS · METHODS · SERVICE · FOR EVERY CLEANING REQUIREMENT

ENDURANCE INSURANCE } Weld Inspection by G-E X-Ray



Sample of butt-welded 6½-inch firebox plate A.70 after face bend test.

Babcock and Wilcox, one of the nation's leading fabricators of welded pressure vessels, recently revealed data on a job that required fabrication of 6½-inch firebox plate into an unfired pressure vessel of unusual design for a highly specialized problem.

Of the numerous complex production problems involved, one was the butt-welding of heavy 6½-inch plates. B&W Fusion Welding Process solved that problem—produced seams that withstood elongation of 45% before tear.

A leader in the use of x-ray inspection to insure flaw-free welds, B&W has long made it routine practice to *x-ray inspect every inch of main welds.* To x-ray the "weld that held" in the 6½-inch plate, B&W used its powerful million-volt G-E X-Ray unit installed at its Barberton, Ohio plant.

First to apply x-ray to industrial inspection, G-E X-Ray has a wide background of diversified experience to help you apply x-ray in your business. To get reliable facts and figures, call in a G-E X-Ray engineer. He will be glad to discuss your problem with you. To request his services, write today to General Electric X-Ray Corporation, 175 Jackson Boulevard, Chicago 4, Illinois, Department 2526.

GENERAL ELECTRIC X-RAY CORPORATION

NELSON ANNOUNCES BRITISH ISLES REPRESENTATION

Manufacturing and distribution rights for Nelson automatic stud-welding equipment and flux-filled studs in the British Isles have been acquired by Cooke & Ferguson, Ltd., of Manchester, according to an announcement by Ted. Nelson, head of Nelson enterprises in the United States.

Arrangements completed this week by Charles C. Henderson, representing Cooke & Ferguson, call for the establishment of complete manufacturing facilities at the firm's headquarters located at Victoria St., Openshaw, Manchester. Complete application engineering, sales and service facilities will be provided throughout the British Isles. The area has been divided into four territories and a field engineering staff, patterned after the Nelson field engineering organization in the United States, will be created to cover all territories.

Cooke & Ferguson, Ltd., are electrical welding engineers and manufacturers with long experience in the field. The Nelson organization, designers and manufacturers of automatic stud-welding equipment invented by Ted Nelson early in the war years, consists of the Nelson Specialty Welding Equipment Corp. at San Leandro, Calif., Nelson Stud Welding Corp., at Lorain, Ohio, and Nelson Sales Corp. representing both previously named manufacturing companies and also headquartered at Lorain, Ohio. Extensively used during the war, Nelson products reached a 9 million dollar volume in 1945. Recent applications in the railroad, automotive and similar industrial fields indicate a substantial increase in postwar volume.

ALL-MANGANESE STEEL WELDED TYPE DIPPERS

To meet demands for a dipper with optimum durability and over-all weight, the American Manganese Steel Division of the American Brake Shoe Co., Chicago Heights, Ill., has introduced the Amsco all-manganese steel welded type dipper.

When fitted with a door and bail of adequately strong design, this dipper is somewhat lighter in weight than the Amsco patented renewable lip dipper, thousands of which have been put into service since 1928. If made with a lightly constructed door and hinges, as generally used in lightweight dippers, it will not exceed the weight of any composite-type fabricated dipper that is sufficiently strong to do a good job. The dipper illustrated, however, has the advantage of having a manganese steel body welded into an operating unit.

Overlapping, rabbeted joints leave grooves for a welded bead. The parts are fitted together with round plugs,

around which likewise weld metal is deposited. Consequently the body of this all-manganese steel dipper is as strong and homogeneous as if made in one piece. At the same time it is possible to remove a worn front and reweld in place a new one without destroying the back.

The Amsco all-manganese steel welded type dipper is made in capacities of $^3/_4$ cu. yd. and up. Sizes $^3/_4$ yd. to 2 yd. are made in two body pieces, front and back. Sizes over 2 yd. are made in four pieces; front, back and two side plates.

More information on this dipper may be obtained from American Manganese Steel Division of American Brake Shoe Co., Chicago Heights, Ill.

DEKKER PROMOTED

G. J. Dekker has been elected a vice-president of the Ohio Chemical & Mfg. Co. according to an announcement by L. A. Hull, president. Mr. Dekker has been

affiliated with Air Reduction, of which The Ohio Chemical & Mfg. Co. is a subsidiary, since 1919. He was appointed assistant manager of the Detroit district in 1931. After serving briefly as manager of the Oklahoma district, in 1940, Mr. Dekker was returned to Detroit as manager. He held this position at the time of his election. Mr. Dekker is a member of the AMERICAN WELDING SOCIETY.

MULLEN APPOINTED MANAGER AMPCO RESISTANCE WELDING SALES

Ray J. Thompson, General Sales Manager, of Ampco Metal, Inc., Milwaukee, Wis., has announced the appointment of Henry A. Mullen as Manager of Resistance Welding Sales. He was formerly Resistance Welding Field Engineer and stationed in Detroit.

Previous to his connection with Ampco, Mullen was Welding Engineer with the Willow Run plant of the Ford Motor Co. His wide experience in the resistance welding field and familiarity with welding problems gives him a perspective that will be beneficial to prospective and present users of Ampcoloy Resistance Welding Electrodes and alloys.

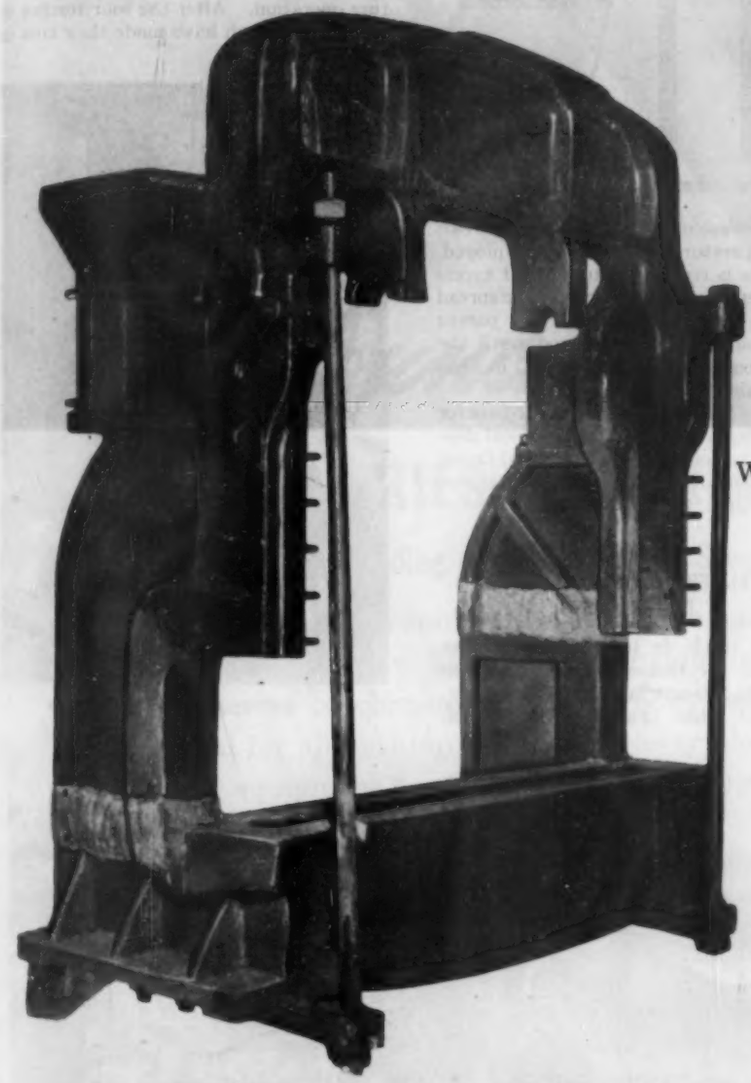
Mr. Mullen is a member of the AMERICAN WELDING SOCIETY.

A.-C. BRONZE ELECTRODE

In line with a desire to give to the arc-welding industry better, more useful electrodes, Ampco Metal, Inc., Milwaukee 4, Wis., has produced a new series of five heavy coated shielded-arc aluminum

"...it would not have been practical to do this job by any other method than *Bronze Welding*"

Ruckman-Hansen, Inc., Fort Wayne, Ind.



Writes Mr. G. W. Laws of Ruckman-Hansen:

"WE are sending you a photograph of a cast iron press frame which was reclaimed by bronze welding in our industrial welding department. This press was completely broken in two.

"The casting as shown weighed approximately 3½ tons. Twenty hours were spent for preparation and sixteen for actual welding. We used 100 lb. of Anaconda 997 (Low-Fuming) Rod.

"*We feel that it would not have been practical to do this job by any other method than bronze welding.*"

This letter tells in a nutshell the story of Bronze Welding. The equally factual story of Anaconda Welding Rods is told in Publication B-13. Write for a copy.

46199

ANACONDA

Anaconda

WELDING RODS

THE AMERICAN BRASS COMPANY

General Offices: Waterbury 88, Connecticut

Subsidiary of Anaconda Copper Mining Company

In Canada: ANACONDA AMERICAN BRASS LTD., *New Toronto, Ont.*

bronze electrodes known as "Ampco-Trode AC." With the increased use of a.-c. welding equipment, these new electrodes offer to those using alternating-current equipment rods suitable for their use. The new electrodes also work splendidly with d.-c. equipment.

A new bulletin W-9 has been issued which describes in detail the five grades of "Ampco-Trode a.-c." electrode. It is well illustrated with photographs, contains a table of physical properties, lists 57 typical applications, and gives outstanding features of the new weldrod. Detailed welding procedures are also published in Bulletin W-9.

The conventional short arc technique of coated steel is used, eliminating the long arc technique usually associated with bronze welding. All position welding is possible as the coating crater and burn-off allows easy manipulation flat, vertical or overhead. Bead contours are smooth, the deposits are dense and pit-free, and spatter loss is low.

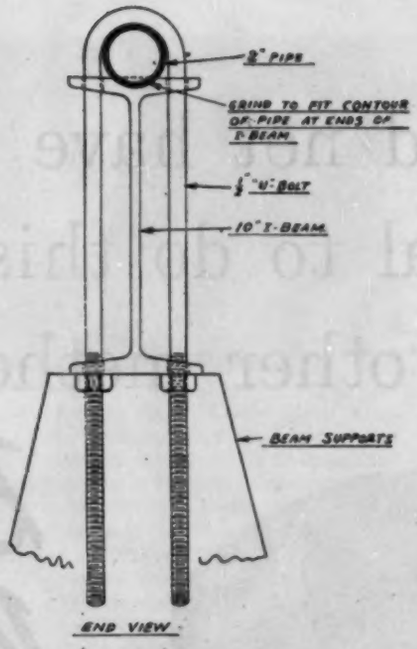
Copies of Bulletin W-9 will be sent on request.

HARD-SURFACING OF ROLLING MILL SKID PIPES

Maintenance of billet-heating furnace skid pipes in rolling mills has been a painfully costly item—one of those conditions for which an effective remedy must be developed sooner or later. The sketch shows the application of Amsco No. 459 Welding Rod, gas-welded, which has increased the life of rolling mill furnace skid pipes from the usual six to eight weeks to 16 to 18 months. Hard-surfacing the pipes with No. 459, adapted to resist severe abrasion, also reduces proportionately the disruptions of production which occur when skid pipes develop leaks from wear.

SECTION THRU HARD FACED SKID PIPE

To reduce surface checking and control warpage when applying No. 459 to skid pipes, prebending of the pipes is recommended. After the skid has been bolted in place on the "I-" beam, that portion of the pipe surface to which the welding rod is to be applied should be ground to remove mill scale, rust, etc. A larger torch tip than for ordinary welding and a neutral oxyacetylene flame to preheat or



bring the base metal to a fusion or sweating temperature should be employed. The flame is readjusted to a slight excess of acetylene and the rod is melted to spread over the sweated surface of the parent metal; adding additional rod until the proper height, approximately $^{3}/_{16}$ in., has been obtained.

Amsco 459, a cast rod, available bare for gas-welding and coated for electrical deposition, is one of several hard-facing materials made by American Manganese Steel Division, Chicago Heights, Ill.

JEEP-WELDER COMBINATION PAYS DIVIDENDS

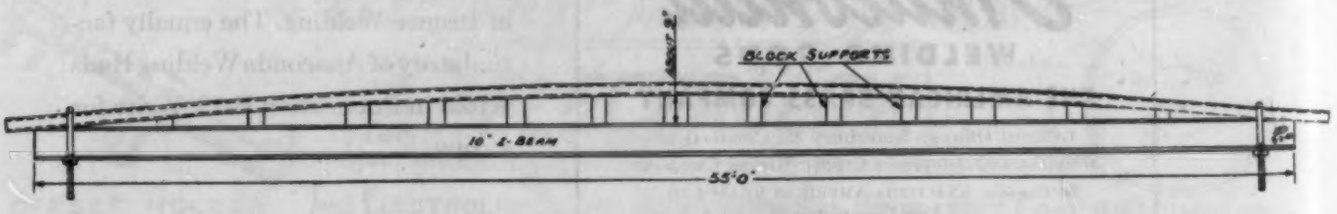
Utility truck de luxe is this civilian version of the famous "Army Jeep" as used on the 200-acre farm of William Durr, Staunton, Ohio. Farmer Durr's son drove one during his four-year hitch in the Army and just couldn't get out of the habit. Besides being used for hauling, pulling and general run-about, this one, together with its detachable welding generator, is used for making speedy repairs to farm equipment at the barn or in the field, wherever a breakdown may occur. The 200-amp. welding generator is securely bolted to the floor and is coupled to the power take-off by four V belts.

ARC WELDING AND FLAME CUTTING AT THE SAME TIME

This photograph, taken at the Service Welding Co. shop in Ridgefield, N. J., shows an interesting method of preventing distortion during a multiple torch cutting operation. After the four torches of the 6A Oxygraph have made their cuts in

Photo, courtesy Air Reduction

Data and Photo. Courtesy The Hobart Brothers Co., Troy, Ohio.



Hard-Surfacing of Rolling Mill Skid Pipes

Announcing

TWO NEW SERIES OF MUREX ELECTRODES

...For All-Position Welding of High-Strength Steels

One of the most important welding developments in recent years, the new Murex line provides two complete series of chrome-moly electrodes especially suited for all-position welding of power plant piping and equipment as well as a variety of applications involving high tensile strength steels.

The graduated alloying contents of chromium and molybdenum give these electrodes a wide range of well-balanced mechanical properties. Thus it is possible to select weld metal similar in strength and ductility to many high tensile steels. The eight electrodes, listed at right, comprise the two groups.

	MUREX TYPE	AWS Grade
...for use on direct current with reverse polarity.	1100	E7010
	2110	E8010
	4110	E9010
	4210	E10010
	MUREX TYPE	**AWS Grade**
...for use on alternating current or direct current with either polarity.	1113	E7013
	2113	E8013
	4113	E9013
	4213	E10013

Write today for more complete information concerning these electrodes.

METAL & THERMIT CORPORATION

120 BROADWAY, NEW YORK 5, N. Y.

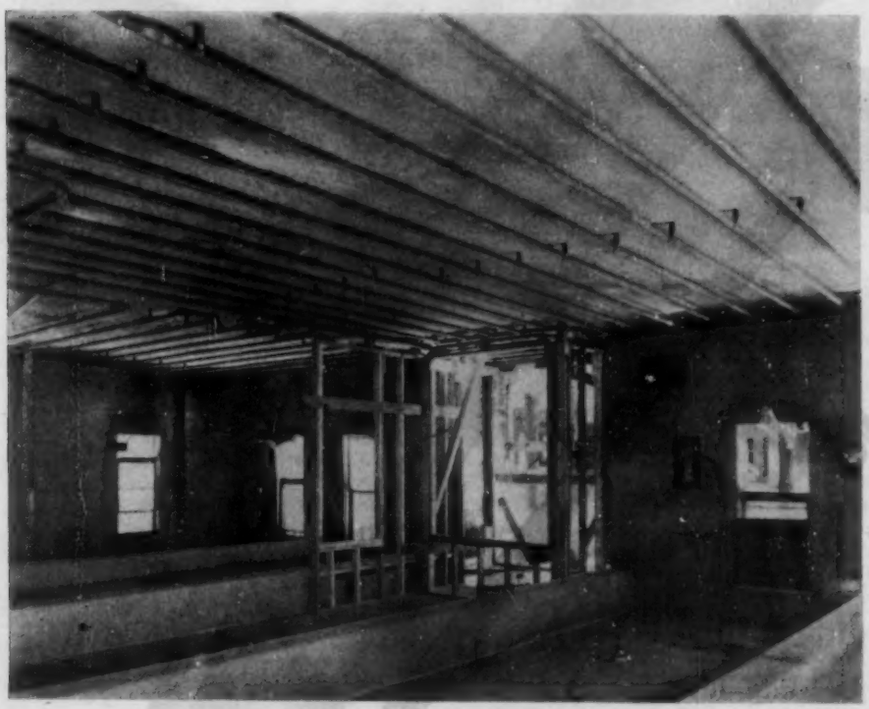
Albany • Chicago • Pittsburgh • So. San Francisco • Toronto

MUREX ELECTRODES

the outer edge of the 1/2-in. steel plate, the welder, using an Airco No. 81 electrode, follows along, making tack welds at the point of entry, thereby restoring the steel to one continuous strip and precluding the possibility of "walking" or "lifting."

RADIANT HEAT

How a radiant heating system may be installed during a remodeling project is illustrated by the photograph of the American Junior Red Cross headquarters building at Erie, Pa. To fabricate the radiant heating system, G. L. Scobell Co., Erie heating contractors, welded 1 1/4-in., 1 1/2-in. and 2-in. wrought iron pipes into a grid and sinuous coils. Short lengths of 1 1/4-in. wrought iron pipe were welded to the bottom of each coil and grid pipe to form legs (see Fig. 1). Then a gravel bed was spread on the existing concrete floor under the radiant heating element (see Fig. 2). A 3-in. concrete slab was poured on the pipes and the gravel fill, and the slab was topped with tile, applied with a mastic. Hot water from a gas-fired boiler is circulated through the system by a 1 1/2-in. pump. A three-way mixing valve is used on the return main to blend heated water with the water returning from the circuit. Occupants have stated that the radiant heating system has achieved an unusually high degree of comfort. The system was designed by B. W. McDowell Co., Erie, in collaboration with Clairence Pulling, Engineer for the City of Erie, who is consultant to the Red Cross.



American Junior Red Cross Headquarters

WELDED SEWAGE LINE

Fabrication technique employed in assembling the sewage outfall line for Seagirt, N. J., involved the use of wrought-iron long-split sleeves, 30 in. long, 14 in. in diameter and 1/2 in. wall thickness. These sleeves were used in coupling the lengths of 12-in. O.D. wrought-iron pipe and were end beveled to facilitate welding and insure watertight connections, extremely important in this service because of the stresses imposed by shifting sands and interior and exterior corrosive action of sewage and salt water, respectively.

Welded Sewage Line

SUSTAINING MEMBER

The Crown Iron Works Co. organized in Minneapolis in 1878 and has operated continuously in the production of ornamental and other fabricated metal products. Today, products include welded steel structures, miscellaneous machinery items, welded steel stoker feed screws, fence products and ornamental and foundry products. During the war the Army-Navy "E" award was earned four times for excellence in production.

Employment Service Bulletin

SERVICES AVAILABLE

A-529. Graduate engineer, age 33, desires administrative position, either manufacturing or engineering, in the welding industry. Extensive knowledge of fundamental and applied science coupled with complete familiarity with sound manufacturing principles governing welding and the allied processes. Experience with problems of welding design, metallurgy, production planning, cost control and shop layout. A comprehensive understanding of fabrication methods gained through employing them, engineering training, and supervisory experience combined into the equipment necessary for competent direction of any phase of the welding industry. Presently concerned with the fabrication of Diesel engine and locomotive weldments. Salary commensurate with responsibilities assumed.

A.S.T.E. CONVENTION

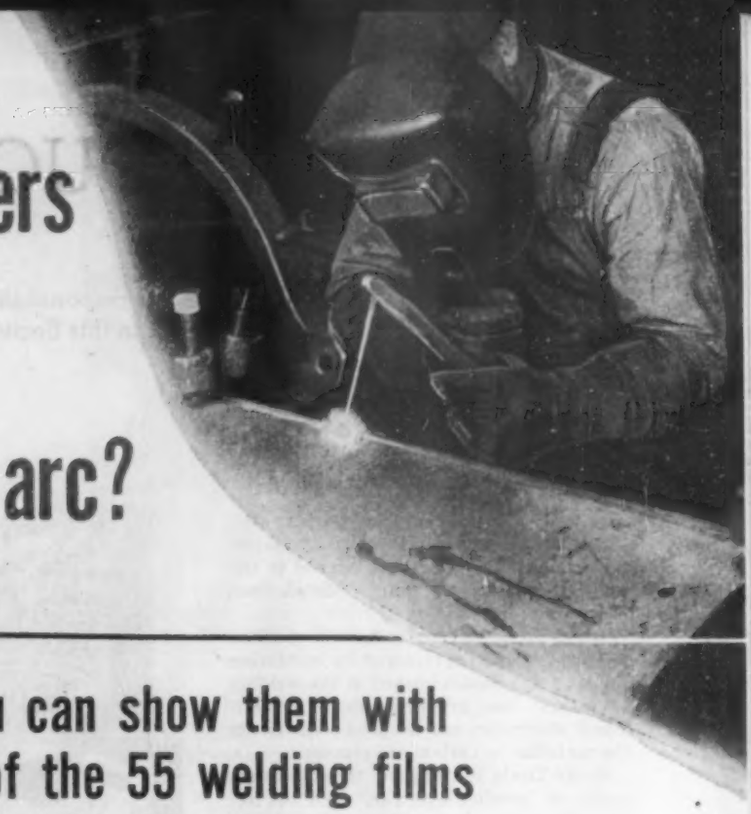
The American Society of Tool Engineers announced through its President, A. M. Sargent, preliminary plans for the largest Semi-Annual National Convention in the Society's history to be held at Pittsburgh, Pennsylvania, October 10-11-12, 1946. Convention headquarters will be the Hotel William Penn where the entire 17th floor has been reserved for scheduled activities.

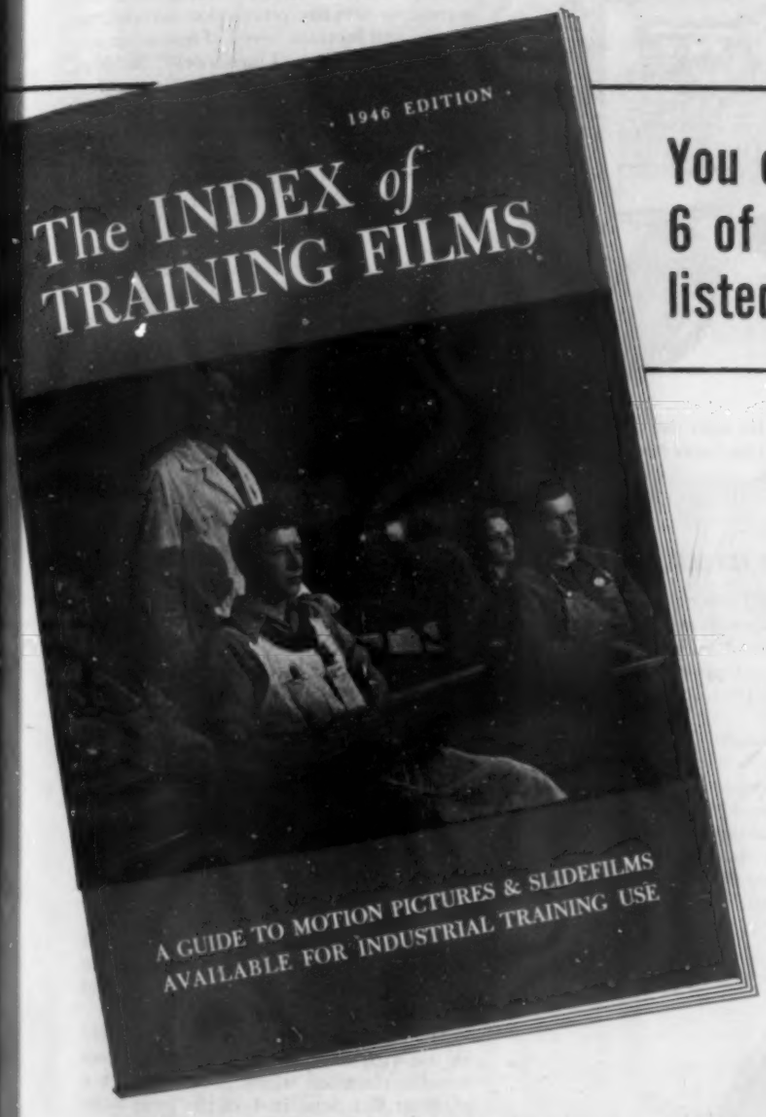
Highlights of the three-day, weekend schedule were made known after a recent meeting of the National Program and Host Chapter Committees in Pittsburgh.

Seminars on timely technical subjects, visits to industrial plants in the Pittsburgh area employing new production techniques, showings of engineering films, the Semi-Annual Banquet, and many special events make up the comprehensive convention agenda, according to Sargent.

On Thursday afternoon, October 10th, there will be a meeting devoted to "Welding and Design."

How many of your welders know what happens inside an arc?





You can show them with 6 of the 55 welding films listed in this new book.

There's nothing like a training film for explaining such details as what goes on inside a welding arc. That's why so many leading welding shops train their welders with the films listed in this book . . . films you can get from manufacturers of welding equipment, film distributors, and government bureaus.

This new book tells you where to get these films . . . which are free . . . which can be rented or bought . . . what they cost.

It describes 55 motion picture and slide films on welding alone . . . covers such subjects as flame cutting, brazing carbide tools, stress relieving, and various forms of welding. In addition there are about 1650 films on other industrial subjects.

You may want to utilize some of these films right away . . . so, write today for your free copy of "The Index of Training Films."

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NEW PRODUCTS

The Society assumes no responsibility for the validity of claims in this Section

WELDING ELECTRODE

A new, coated beryllium-copper electrode, known as Beryl-Trode, is the latest copper-base alloy electrode offered to the welding industry by Ampco Metal, Inc., Milwaukee 4, Wis.

Beryl-Trode electrodes have a medium weight, flux coating required for stabilizing the arc; flux oxides formed in the welding operation; and produce a dense deposit. These electrodes can be used with either the metallic- or carbon-arc process.

Beryl-Trode is designed to weld parts made of beryllium-copper, such as, resistance welding jaws, seam welder wheels, etc. The deposits, when heat treated, develop high-hardness, high-strength values similar to the base metal. These electrodes are used for joining, repairing cracks or defects in castings and for building up of worn surfaces.

Beryl-Trode electrodes are made in two diameters only—5/32 and 3/16 in. in 14 in.-lengths.

Additional information and prices on request.

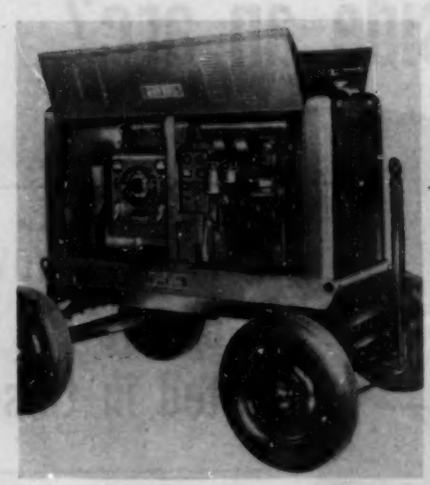
DIESEL ENGINE-DRIVEN ARC WELDER

The newest addition to the Hobart "Multi-Range" welder line is a Diesel engine driven arc welder of 300 amp. capacity, especially made for use in locations where electric power is not available and a minimum operating cost is desired.

Equipped with patented "Multi-Range" Dual Control and exclusive remote control, this new welder permits the operator to make fine volt-ampere adjustments right at the work, eliminating unnecessary steps from work to machine and back to work. Its 1000 combinations of voltage and amperage permit the operator to select the right arc intensity to suit any job. Other features of the welding generator include separate excitation and two-way ventilation, for a smoother, more productive arc at all current values.

The welding generator has a rating of 300 amp. at 40 v. Current range for welding duty is from 20 to 40 v., 60 to 375 amp. It is a single-operator variable voltage type, with 4 laminated main poles and four interpoles (commutating poles). Pole pieces are removable. This unit also has oversize, 4-pole exciter built in on main shaft that insures quick arc recovery and build-up, and eliminates accidental polarity reversal.

This new 300-amp. diesel engine driven welder (stationary model) weighs 2637 lb. dry and can be readily mounted on wheels,



trailer or truck for easy portability. Optional equipment includes pneumatic tired 4-wheeled trailer.

ALL-PURPOSE ELECTRODE HOLDER

This new electrode holder, product of the Garibay Manufacturing Co., offers many practical improvements in design to increase welding efficiency by 20%.

It is full insulated, and known as the Garibay "350."

It is light in weight (17 oz.), simple and compact for ease in manipulation. Carries 350 amp. continuous conductivity.

Offset jaws provide a full view of work at all times, making welding possible in places ordinarily inaccessible. It uses all the coated portion of the electrode. Bending of the rod and breaking the flux are never necessary. Full throat construction provides easy flow of electricity with a minimum of resistance. Scientifically ventilated for cool handling. Equipped with a mechanical cable connector which does away with the slow solder method.

The company also makes the Garibay "Stinger" Electrode Holder, a popular, all-purpose, light weight holder for uses where full insulation is unnecessary. Garibay Manufacturing Co., 1517 Colegrove Ave., Montebello, Calif.

IMPROVEMENTS ANNOUNCED ON AUTOMATIC WELDING HEAD

Improvements of its welding head designed to simplify production installation setups and increase speed of operation are announced for its "Lincolnweld" hidden-arc process of automatic metallic shielded arc welding by The Lincoln Electric Co., Cleveland, Ohio. The new, improved head is designated as the "LAF-2."

To further expand its use on sheet metal work, the "LAF-2" has been designed to accommodate 3/32-in. electrode. The head is shipped with the same lower wire contact jaws as the previous head designated as "LAF-1" which accommodates electrode wire ranging from 1/8 in. to 7/32 in., but an extra movable tapered contact jaw is supplied which can be quickly interchanged if 3/32-in. wire is desired.

The controls of the "LAF-2" have been modified to simplify arc starting. Now all that is required to start the arc is to turn a single control switch to the "Down Weld" position. This causes the electrode to feed down until the end touches the work piece. Short circuiting the wire to the plate automatically causes the wire feed motor to stop. The flux valve is then turned on and the arc started by means of a push button. The arc is extinguished and the electrode is withdrawn by moving the operating switch from "Down Weld" to the "Up" position.

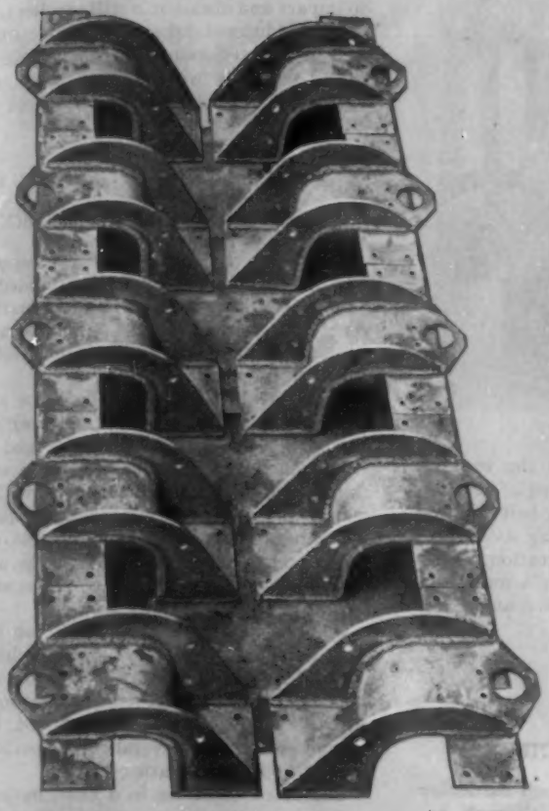
Another innovation is the use of plugs and receptacles which simplify and radically reduce installation time for the "LAF-2" head. Two receptacles are mounted in the automatic control box and plugs are attached to one end of the cable coming from the welder supply and one end of the cable coming from the head itself.

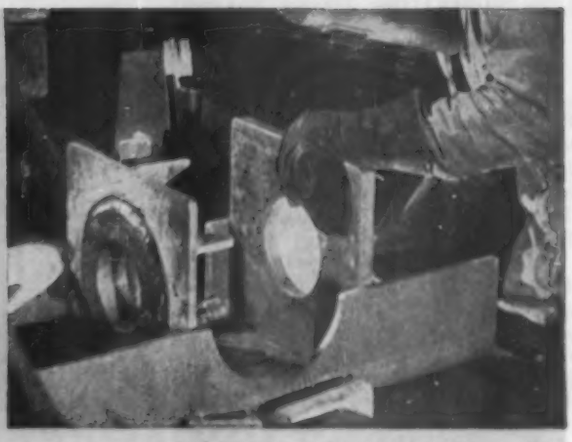
A new, simplified wire straightener has also been added which makes it easier to insert the starting end of the wire and effect more positive wire straightening.

The "Lincolnweld" process is designed for use with direct current, utilizing a bare metallic electrode which is fed through a granular flux deposited on the joint to be welded. Sufficient flux is applied to completely cover the arc and the molten metal; the unfused flux is then reclaimed for further use.

It has been successfully used in welding all types of joints including plug, butt, lap, edge, fillet and corner.

ANNUAL MEETING
ATLANTIC CITY
NOV. 17—22





FOR TACK WELDING — in any position—3/16" AP gives perfect results; quick, deep penetration, eliminating humps.

FOR INDUSTRIAL FABRICATION — in volume production, 3/16" AP provides fast downhand deposition and enables the operator to switch to vertical and overhead work without stopping to change electrodes.

FOR PIPE WELDING — here again, 3/16" AP is a big money-saver for butt welding and joining all types of fittings with its smooth-flowing, deep penetrating arc.

CALL YOUR P&H REPRESENTATIVE

P&H makes a production-proved electrode for every welding requirement: for all mild, alloy and stainless steel applications, cast iron and for building up and hard surfacing.

ON CONSTRUCTION WORK— 3/16" AP ends the need for frequent time-wasting changes to smaller electrodes when working from downhand to out-of-position welds.

P&H WELDING ELECTRODES

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Milwaukee 14, Wisconsin

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AMERICA'S MOST COMPLETE ARC WELDING SERVICE

DC Welders

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Welding Electrodes

Welding Positioners

Welding Production Control Systems

Electric Hoists

LOW-TEMPERATURE SILVER BRAZING ALLOYS

With the price of silver increased approximately 20 cents per troy ounce the two new silver-brazing alloys featuring lower silver content just announced by Handy & Harman should be of great interest to everybody working in metals. The new alloys are called Easy-Flo 45 and Easy-Flo 35.

As its name implies, Easy-Flo 45 is a 45% silver alloy. In addition, it contains copper, zinc and cadmium. One of its exceptional features is a new, low-melting range—1120° F. to 1145° F. The joints produced between ferrous, nonferrous and dissimilar metals are strong, ductile, leak-tight. It offers the full advantages of alloys with a higher silver content but due to less silver in its composition provides an economy to help offset the increase in the price of silver.

The 35% alloy has characteristics quite different from Easy-Flo 45. It has wider melting range—1115° F. to 1295° F.—and is free flowing at an exceptionally low temperature for an alloy containing 35% silver. It offers an opportunity for manufacturers to economically produce joints between ferrous or nonferrous metals which are high in strength and ductility and is appropriate to use in places where a higher working temperature is not objectionable.

These two alloys have been developed in the Handy & Harman laboratories during the past two years. They are the most recent creation of a continuous research through which this manufacturer is constantly seeking to provide industry with the best alloys that can be developed to further the use of this popular method of metal joining. Complete details about the new Easy-Flo 45 and 35 can be obtained from Handy & Harman, 82 Fulton St., New York 7, N. Y.

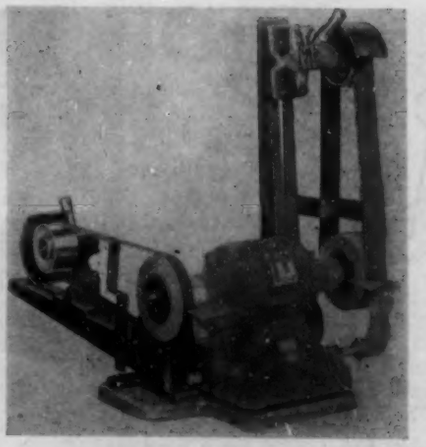
LIGHT BELT GRINDER ATTACHMENT

The Porter-Cable Machine Co. of Syracuse, N. Y., announces a new addition to its line of abrasive belt grinders.

A light, narrow belt grinder attachment, type N-2, has been developed capable of performing all kinds of light burring and grinding operations. Combining the versatility of platen grinding with the economy and speed of contact grinding it is ideal for light grinding of flats, arcs, angles, gear burring, weld grinding, cleaning up operations, etc. A wide variety of composition and plastic materials, as well as steel, iron, aluminum, wood and glass are easily ground and surfaced.

The attachment is furnished without motor and is quickly aligned and attached to the familiar bench-type wheel grinder, to which a resilient contact roll has been fitted.

The complete unit assembly stands 27 in. high with a width of 2½ in. A 6- x 7-in., T-shape base is drilled with 3 holes for convenient mounting to bench or work table. Platen size for flat grinding is 2 x 4 in. Resilient contact rolls 2 x 6 in. or 1 × 6 in. can be furnished. Using an endless abrasive belt 2 x 48 in. the attachment can be used either in the vertical, horizontal or any position (angle) between the 90 degrees. The abrasive belt grinding method assures faster cutting as well as cool and vibrationless operation. Belt changing is accomplished in a matter of seconds eliminating expensive and time-consuming wheel dressing.



SELF-HARDENING ELECTRODES

A new extrusion coated self-hardening electrode is now available through authorized Airco dealers from coast to coast.

Manufactured by the Stoody Co., this versatile electrode embraces excellent arc characteristics, working equally as well with either an a.-c. or d.-c. machine. This new extruded coating is much stronger, has less tendency to pick up moisture, presents a better appearance, and above all, is completely uniform. The new extruded Stoody self-hardening electrode has many other advantages. Briefly enumerated, the following emphasize the more important properties:

1. No slag interference.
2. More rapid deposition rate than dipped-type electrodes.
3. Can be applied in all positions.
4. No loss of hardness or wear resistance on multiple layers.
5. Solid, dense deposits with an absolute minimum of porosity.
6. Satisfactory application within a wide range of amperages.
7. Easy slag removal while deposit is still red hot—slag is self-lifting when deposits cool.
8. Any desired type of bead can be applied including stringers, figure eights, crescents, weaving beads, etc.

Typical applications of the new Stoody self-hardening electrode include hard facing in building up worn areas of tractor lugs, shovel teeth, manganese steel crushing equipment, hampers, dredge pump casings, wobblers, clutches, spindles, coupling boxes, bulldozer blades and various other equipment.

Because the analysis of the new coated Stoody self-hardening electrode remains unchanged, its physical properties and deposits are the same as those of the dipped-coating electrode. Its resistance to impact and abrasion is still excellent.

For additional information concerning this new development, consult nearest Airco dealer or write to Air Reduction Sales Co., 60 E. 42nd Street, New York 17, N. Y.

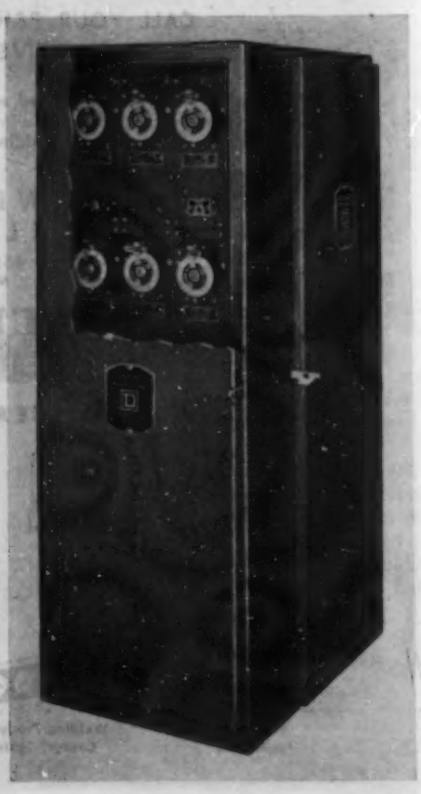
COMBINATION WELDER CONTROL

Fully automatic control of air-operated resistance welding machines is provided in Square D's new Class 8992 combination control unit, designed to meet recently adopted N.E.M.A. Standards for resistance welder control.

A Syncro-Break welder contactor and Safront sequence-weld timer are both included in a single enclosure arranged to mount on the right-hand side of the machine with all control elements within easy reach of operator. More convenient adjustment, better appearance, less expensive and more flexible installation, and safer operation are advantages presented by the manufacturer.

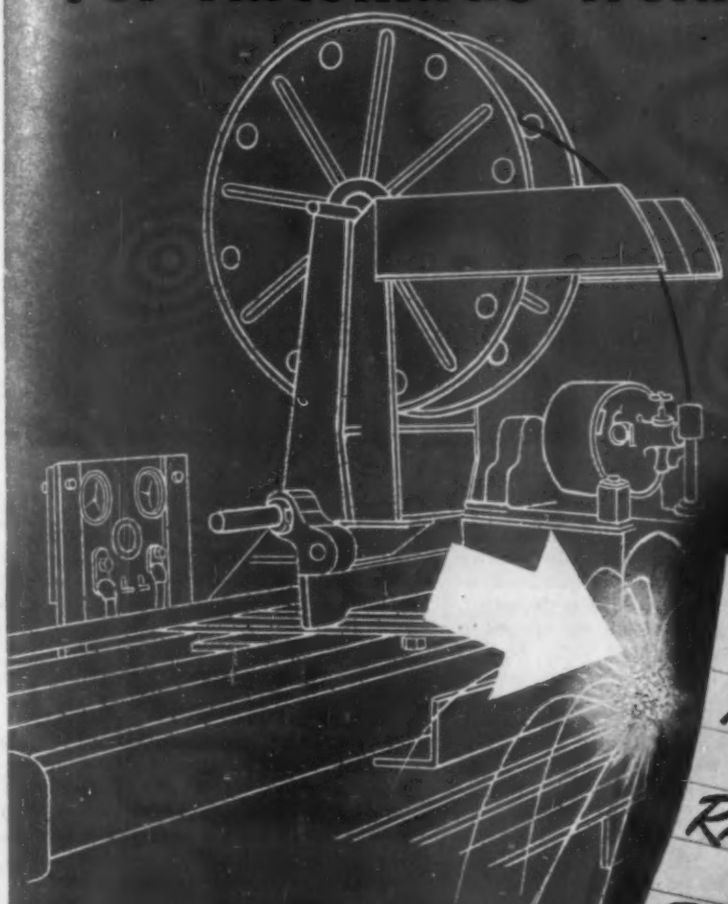
Combination controllers mount on the right-hand side of the welding machine, placing the large calibrated dials on the front of the unit within reach of the operator. Minimum time is required for changing any of the several timing periods making up the automatic cycle.

Unified construction in a neat, modern enclosure makes unnecessary the unsightly wires that run between the several separate control boxes usually mounted at various locations on the welding machine. Physical arrangement and dimensions are in accordance with the latest N.E.M.A. Standards based on suggestions and requirements of resistance welder manufacturers and machinery users.



For Automatic Welding Use these

RACO ELECTRODES



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RACO TYPE D-E-4520
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RACO-BARE OR COPPER COATED WIRE FOR SUBMERGED ARC WELDING

Wherever these electrodes are used low-cost, high-quality welds result. This is the experience of every manufacturer who has put RACO Automatic Electrodes to work. These electrodes are highest quality — they are unusually fast, and produce welds that are clean, strong and sound. Write today for complete data.

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SINCE 1919 PRODUCERS OF ARC WELDING ELECTRODES AND WELDING RODS

Combination controllers are designed with a control circuit which may be either separate or common with the power circuit. Solenoid air valve may be energized from either the power or control supply sources by simple reconnection. Standard controllers have tapped primary control transformers which can be connected for operation at 110, 220 or 440 v., 60 cycles; or for 380 v., 50 cycles. Other voltages and frequencies are available on special order.

Descriptive literature is available through the Square D Co., 4041 N. Richards St., Milwaukee 12, Wis.

ARC STRIKE WELDER

Two Indianapolis engineers, W. F. Sully and Ray Millholland, have been conducting a private research program in arc welding for the past three years. According to these two investigators, they have developed a unique electrical effect from a radically different type of transformer which they call a phase displacement effect that has shown unusual results as a small 115 v., a.-c. arc welder.

The laboratory model of this new welder is rated by its designers as having a heat range of from 12 to 75 amp., with a current drain from the 115 v., a.-c. supply line of 25 amp. at maximum heat. The power factor at maximum rating is in excess of 0.90 of unity, which is obtained without the use of capacitors or other power factor correcting devices.

Low open circuit voltages are employed, according to the designers, ranging from 36–38 v., at maximum heat, to 53–55 v. for the 12–15 low ampere range. These are the voltages governing the transformation ratio of the transformer, but the inventors state that from oscilloscope observations while welding that the phase displacement effect they obtain enables them to maintain the welding arc with coated electrodes already now on the market and widely distributed.

A feature stressed by the designers is the fact that the arc strike is accomplished by a continuous downward movement of the electrode, and that when the tip of the electrode approaches the work within the normal welding arc gap, the arc automatically starts, without the electrode ever coming in short-circuit contact with the work.

The minimum thickness of steel sheet reported by the designers to have been effectively welded is 0.018 when using a $^1/_{16}$ in. diam. coated electrode of a widely distributed brand. Figure 1 is a panel $2^3/_4$ in. x $1^1/_2$ in. of $^1/_8$-in. one-pass cold-rolled mild steel on which 25 arc-start beads have been deposited. The electrode tip was advanced downward toward the work until the arc discharge automatically took place; then the electrode was halted and allowed to melt off until the arc was broken. A $^3/_{32}$ diam. coated electrode was used, and the open circuit voltage was 34 volts. A duplicate of the electrode employed was also melted its full length without arc stoppage.

Figure 2 is a panel of cold-rolled mild steel $1^1/_8$ in. x 3 in. x 0.0195 in. thickness on which five arc-starting beads have been deposited. The panel rested on a $^1/_8$-in. thick copper contact plate but was not clamped down, but had only gravity contact. The panel was quenched in cold water after each bead was deposited, and the tip of the electrode was clipped to bare metal that projected $^1/_{16}$ in. beyond the coating.

Fig. 1

Fig. 2

Fig. 3

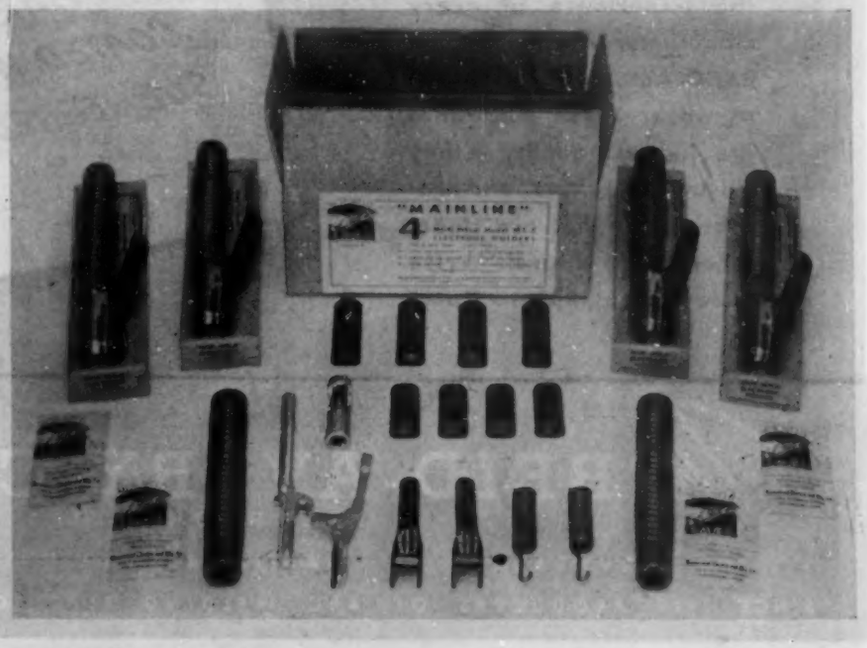
Figure 3 is an arc-start bead deposited upon a $^3/_4$ in. x $^3/_4$ in. x $^1/_{32}$-in. thick square of black annealed sheet steel. The electrode used was the bare piece of punch press scrap, shown tack-welded to the panel. The panel rested by gravity alone upon the work table when the bead was laid.

In all tests for arc starting, in Figs. 1, 2 and 3, the arc was struck on cold metal, with the tip of the electrode freshly clipped, and, in the case of coated electrodes, at least $^1/_{16}$ in. of the bare wire extending beyond the coating.

The designers have patents pending on all features of their arc-welding system and report that they are now negotiating to license its manufacture and sale by some company already established in the welding machine industry.

WELDING SERVICE UNIT

Moorewood Electric and Manufacturing Co., 1718 E. Florence Ave., Los Angeles 1, Calif., announces the immediate availability of a new "Mainline" Welding Service Unit. This kit is the answer to the findings of extensive breakdown tests which determined the exact proportion of replacement parts needed per set of 4 welding units to keep them in continuous operation. It consists of 4 "Mor-Weld" electrode holders, 2 grip handles, 4 upper-jaw insulations, 4 lower-jaw insulations, 2 lever handles, 2 springs, 1 upper jaw, 1 lower jaw, 1 connector core, 1 setscrews, and 1 wrench.



PAGE *Welding* ELECTRODES

Here's ANOTHER New One

Hi-Tensile "M" Shielded Arc

...for welding Low Alloy Steels which have heretofore had to be preheated to avoid underbead cracking during the welding process

This new PAGE Electrode may help simplify some of your welding jobs. The PAGE distributor in your territory can give you complete information about it. He can also tell you what you want to know about any other type of electrode or gas welding rod – of which PAGE offers a complete line.

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ABSTRACTS OF CURRENT WELDING PATENTS

Prepared by V. L. Oldham

Printed copies of patents may be obtained for 25¢ from the Commissioner of Patents, Washington 25, D. C.

2,402,535—AUXILIARY JAW ELECTRODE HOLDER; Everett H. Cushman, Inventor; New York, N. Y.; assignor to Air Reduction Co., Inc. *9 Claims.*

Cushman's electrode holder includes an upper jaw, a lower jaw and an auxiliary jaw of insulating material having portions extending along the sides of the lower jaw.

2,402,646—WELDING ELECTRODE; Chester F. Leathers, *Inventor;* Detroit, Mich. *5 Claims.*

The patent covers a heating element for conducting heating current that passes through the work and the element has a body and a work engaging tip which cooperate to define a coolant circuit through the element. Sealing means holds the body and tip together and prevents leakage of coolant therebetween.

2,402,659—STUD FOR WELDING; Ted Nelson, *Inventor;* San Leandro, Calif. *3 Claims.*

The patented stud has a recess in its end with flux in the recess and a cap over the recess to confine the flux. A centrally disposed point is formed on the cap to facilitate placing the stud.

2,402,820—WELDER'S MASK; William H. Kitchen, *Inventor;* Seattle, Wash. *4 Claims.*

In this patent, an open welder's mask is shown, which mask has air supply means connected thereto, including a tube extending across the inside face of the mask and having upwardly and downwardly directed openings formed therein.

2,402,937—APPARATUS FOR ARC WELDING; Leonidas K. Stringham, *Inventor;* University Heights, Ohio; assignor to The Lincoln Electric Co. *8 Claims.*

Stringham's patent discloses a support with a flexible tube hanging therefrom, and an electrode extending downwardly through the tube. Means are provided to supply granular fluxing material in freely falling condition through the tube without accumulating therein.

2,402,938—ARC WELDING; Leonidas K. Stringham, *Inventor;* University Heights, Ohio; assignor to The Lincoln Electric Co. *10 Claims.*

This patent covers a method relating to Patent 2,402,937 and it includes moving the end of a weld rod relatively of the work to cause the weld rod to traverse the line to be welded, and simultaneously depositing granular flux material along such line. The depth of the deposited flux layer is dependent on the relative movement of the weld rod and work.

2,403,049—METHOD OF MAKING CRANKSHAFTS BY ELECTRIC WELDING; Fritz A. Carstens, *Inventor;* Milwaukee, Wis.; assignor to A. O. Smith Corp. *3 Claims.*

This novel method comprises providing a welding dam spacing the faces of corresponding pin stubs of two cheek units of separately forged parts of a large crankshaft, which dam forms two substantially equal welding grooves. The method then provides that weld metal be deposited in the groove above the dam and be fused to the metal forming the groove's sidewalls as the units are rotated to position the grooves alternately in the uppermost position.

2,403,076—ELECTRIC FLASH WELDING; William C. Heath, *Inventor;* Shorewood, Wis.; assignor to A. O. Smith Corp. *3 Claims.*

Heath's method relates to the welding of a V-shaped edge piece to a foil in the production of an airplane propeller and it includes the steps of forging temporary integral projections on the peak of the edge piece and connecting the welding electrode to such projections for flash welding a foil to the edge piece.

2,403,086—ELECTRODE HOLDER; Max S. Kenworthy, *Inventor;* Portland, Ore.; assignor to C. H. Harsch. *2 Claims.*

In this electrode holder, spring-actuated gripping members are provided to secure the electrode, and a spring-actuated handle also is provided with the members and handle being actuated by a common member.

2,403,109—METHOD OF BRAZING; Mike A. Miller, *Inventor;* New Kensington, Pa.; assignor to Aluminum Co. of America. *2 Claims.*

In this brazing method, the articles to be brazed are immersed in a molten brazing flux which largely comprises the fluorides and chlorides of alkali metals. The flux bath is in contact with a member in which nickel is present and the novelty of the patent relates to providing about 0.5 to 10% by weight nickel particles in the nickel particle-flux mixture.

2,403,221—WELDING APPARATUS; Cecil D. Howard, *Inventor;* Swarthmore, Pa.; assignor to Sun Shipbuilding & Dry Dock Co. *5 Claims.*

The patented apparatus is for butt-welding plates and includes a trolley supported above the plates to be welded and adapted to move longitudinally of the plates. A pair of roller arms are pivotally carried by the trolley and are adapted to bear on the abutted plates, and a welding device is supported for operation between the roller arms.

2,403,229—ELECTRIC RESISTANCE WELDING; Thomas E. Murray, Southampton, George H. Phelps, Floral Park, and George Frischmann, Queens Village, N. Y., *Inventors;* said Murray assignor to Yarrum, Inc., and said Phelps and Frischmann assignors to Murray Manufacturing Corp. *4 Claims.*

This resistance welding apparatus includes electrodes for effecting a weld, and means for removing the burr extruded during the welding operation. The burr removing means includes a cutting tool, and means for moving the tool in a plurality of directions with relation to the electrodes.

2,403,438—WELDING METHOD; Grover A. Hughes, *Inventor;* Seattle, Wash. *2 Claims.*

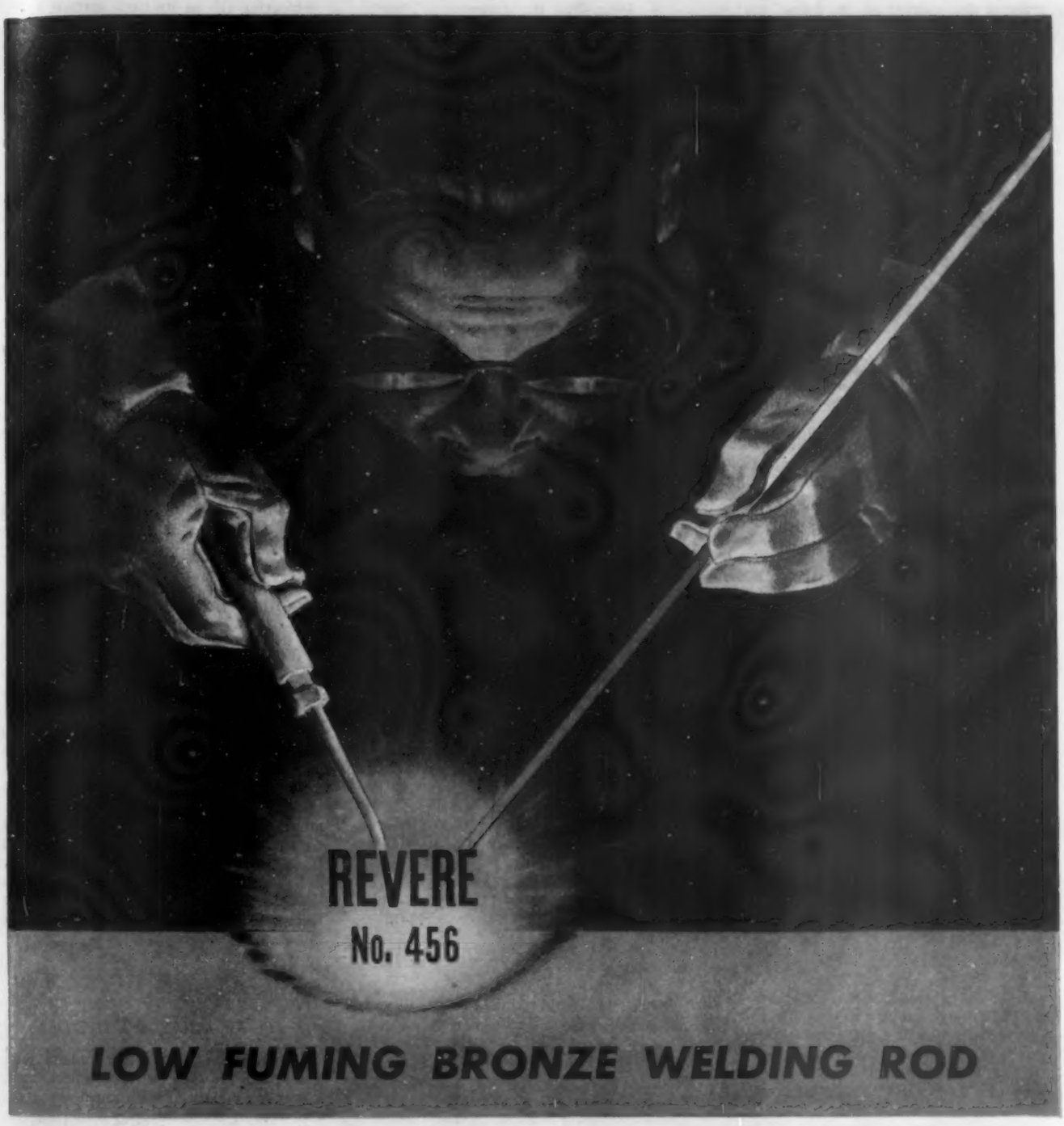
This welding method relates to bonding the head of a headed stub to a metal body and it includes the steps of establishing a suitable arc between the head and the body to effect rapid local fusion of the metal of the body in an area greater than the shank of the stud and thrusting the head into the fused metal before such metal is displaced by gravity. On cooling, a larger area bond is obtained than the cross section of the shank.

2,403,654—WELDER'S ARMREST; August G. Gerdes, *Inventor;* Clinton, Iowa. *5 Claims.*

The armrest disclosed in this patent comprises a resiliently expansible arm support which is supported from the body of the user. The arm support may be inverted with respect to its supporting means.

2,404,028—ELECTRIC WELDING ROD HOLDER; Albert De Wain Best, *Inventor;* Sandusky, Ohio. *1 Claim.*

Best's holder has a stationary jaw on the frame and a movable jaw pivoted, intermediate its ends, on the frame. A pivotal



. . . for quick, strong welds

In maintenance and repair work, in reclaiming worn or broken machine parts, you will find Revere No. 456 "Flame Tested" Bronze Welding Rod easy to handle and use. You get *minimum fuming*, quick, strong welds, and you save time and fuel. The low melting point of this Revere rod cuts down the need for high pre-heats and post-heating usually necessary in the straight fusion welding of cast iron. It is suitable for the bronze welding of cast and malleable irons, wrought iron, cast and wrought steel, as well as cast and wrought bronze.

Other Revere Welding Rods are: Revere Bronze 380; Revere Manganese Bronze; Herculoy; Revere Phosphor Bronzes; Revere Brass (Brazing Rod); Revere Silicon Deoxidized Copper; Revere Phosphor Deoxidized Copper; and Revere Electrolytic Copper. These Revere Welding Rods come in 100-pound cases or in 25-pound cartons, net weight. Handled by Revere Welding Rod Distributors in all parts of the country. Write for folder giving technical data and net prices.

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lever is also carried on the frame, and it has a cam thereon for engaging with the movable jaw for positioning same.

2,404,125—ELECTRODE HOLDER; Thomas S. Donnelly, Jr., *Inventor;* Detroit, Mich.; assignor to Bordon Mfg. Co. *3 Claims.*

In this patented electrode holder, the electrode clamping jaw has an outwardly projecting rib on its back surface, and a relatively wide insulation plate has a groove that engages with the rib to secure the jaw and plate together.

SECTION ACTIVITIES

CLEVELAND

The following committee chairmen for the 1946–47 season have been appointed by the Cleveland Section.

Heading the list is Michael Shane, Chairman of the Papers and Program Committee. Mike is also Vice-Chairman of the Section. Chairman of the Annual Symposium is 2nd Vice-Chairman Arthur G. Portz.

Other operating committee chairmen are as follows: Dinner, Kenneth MacPherson; Reception, J. Calvin Wyss; Code, J. Frank Maine; Nominating, Ross J. Yarrow; Constitution and By-Laws, Edward T. Scott; Education, John Kincaid; Properties, Ken Wood; Publicity, John R. Morrill; Auditing, Ross J. Yarrow; Tellers, Robert J. Kriz.

The Advisory Committee Chairmen are as follows: Sponsors, J. T. Wolfenden; Resistance Welders, Harold Card; Arc Welders, John R. Morrill; Fabricators, J. L. Mooney; Engineers, C. Merrill Barber; Metallurgy, Earle C. Smith; Marine, Andrew B. Smith; Inter-Society Program Coordination, Clayton T. Elder.

INLAND EMPIRE

A newly formed Section to be known as the "Inland Empire" Section held its organization meeting on June 25th and elected the following officers:

Chairman, Thomas S. Sholes; *Vice-Chairman,* Eugene B. LaVelle; *Secretary-Treasurer,* Ellsworth L. Reynolds. *Committeemen at large,* (two-year term) Fred Fait, Lennis A. Kile, Walter Pentz; (one-year term) Roland Johnson, Les Blackford, Stewart J. Scott.

Professor Gilbert S. Schaller, of the University of Washington, delivered a particularly fine and greatly appreciated lecture relative to the metallurgical aspects of welding at this meeting.

DETROIT

At the last Executive Committee meeting of the Detroit Section and the Saginaw Division of the Detroit Section on June 14th, George N. Sieger retired as Secretary and Treasurer of the Section and was succeeded by Ed Brown of the American Brass Company. Mr. Sieger was presented with a traveling bag in appreciation of the excellent work he has done as officer of the Detroit Section for the past six years, and it was pointed out that in 1940 Detroit was eighteenth in national standing with an active membership of 85, and rose to first place in 1945, with an active membership of 494. The Section feels that a good part of this growth is due to the wholehearted effort of Mr. Sieger.

NEW JERSEY

Officers and Executive Committee of New Jersey Section for 1946–47 are as follows:

Chairman, R. M. Wilson, International Nickel Co.; *Vice-Chairman,* R. T. Pursell, East Orange, N. J.; *Secretary-Treasurer,* P. M. Mattern, Wilson Welder & Metals Co. *Executive Committee:* J. W. Goolliffe, F. B. Swankhous, W. B. Bunn, G. W. Nigh, J. D. Dyer, C. D. Cooper, J. E. Gunning, Allen B. Kime, J. D. Bluhm, H. R. Steffins. *Chairmen of Special Committees:* Program, W. B. Bunn; Membership, J. D. Bluhm; Advisory, M. F. Sheely; Advertising, J. D. Dyer; Publicity, R. T. Pursell.

ROCHESTER

At the Annual Meeting of the Rochester Section the following officers were elected.

Chairman, Joseph O'Rorke, Eastman Kodak Co.; *Vice-Chairman,* Harold King, The Anstice Co.; *Secretary,* Edward Jones, Seneca Steel Service Inc. *Executive Committee:* Paul Ecklund, Herbert Fetter, Walter Kazoroski, Robert Raudebaugh, Larry Smith, Walter Dick.

SAN FRANCISCO

The San Francisco Section held its final dinner meeting of the 1945–46 season at the Engineers Club, May 27th. Some sixty members and guests attended. Installation of Officers and Committees for the coming year was as follows:

Chairman, Mark Haines, Mark Haines Welding Shop; *Vice-Chairman,* L. P. Henderson, The Lincoln Electric Co.; *Second Vice-Chairman,* F. T. Patton, Standard Oil Co. of Calif.; *Secretary,* R. E. Labagh, Victor Equipment Co.; *Treasurer,* P. H. Bertola, Harnischfeger Corp. *Executive Committee Members:* Leo Berner, Charles S. Smith, Harold L. Saunders. *Committee Chairmen:* Membership, Mark Cassimus; Publicity, Ralph Dodge; Program, Prof. Merle Randall; Public Relations, A. E. Atkinson; Technical, R. E. Gauthier; Educational, Robt. S. Hale; Structural, Sid Baumberger; By-Laws, C. S. Smith; Metals Show Cooperation, Ed Bartz.

WASHINGTON

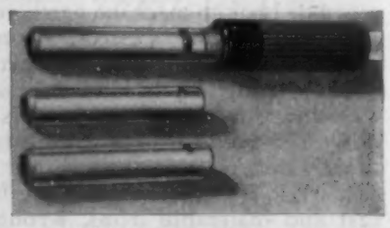
The first Executive Committee meeting of the Washington Section was held at the Westinghouse Offices on July 9th. The following committees were appointed for the new season:

Publicity, R. P. McMillan plus two others; *Membership,* E. L. Akerley plus one; *Program,* G. B. Grable and W. P. Roberts; *By-Laws,* S. W. Trainer and C. J. Eiwen; *D. C. Council,* H. L. Whittemore continued with A. W. Lubbers as alternate; *Educational,* H. L. Ingram and E. M. MacCutcheon.

As in the past, meetings will be held on the last Tuesday of the month, except in December, when it will be scheduled for the week of the 9th.

AIR-ACETYLENE TIPS

Development of an attachment with which, it is claimed by the manufacturer, it is easy to adapt any standard oxyacetylene welding torch for body soldering, tinning and light brazing with an acetylene-air flame, is announced by the Acet-A-Tip Co., 5069 W. Madison St., Chicago 44, Ill.



Acet-A-Tips are attached to the welding torch tip by means of a base, fitted with a 2-in. length of heavy-duty two-ply hose. The hose is forced over the welding torch tip, providing quick, positive attachment.

Acet-A-Tips are available from leading welding equipment jobbers.

Los Angeles Times 9 AM FINAL

1280-Mile Gas Line Authorized

Project Will Cost $70,000,000 to Bring Texas Fuel Here

A 1280-mile, $70,000,000 pipe line to bring natural gas here from Texas and New Mexico has been authorized by the Federal Power Commission, officials of two gas companies in Los Angeles were informed yesterday.

The pipe-line facilities are designed to meet a developing shortage in the local natural gas supply for 3,500,000 persons in California. F.P.C.

Berkeley Continuous

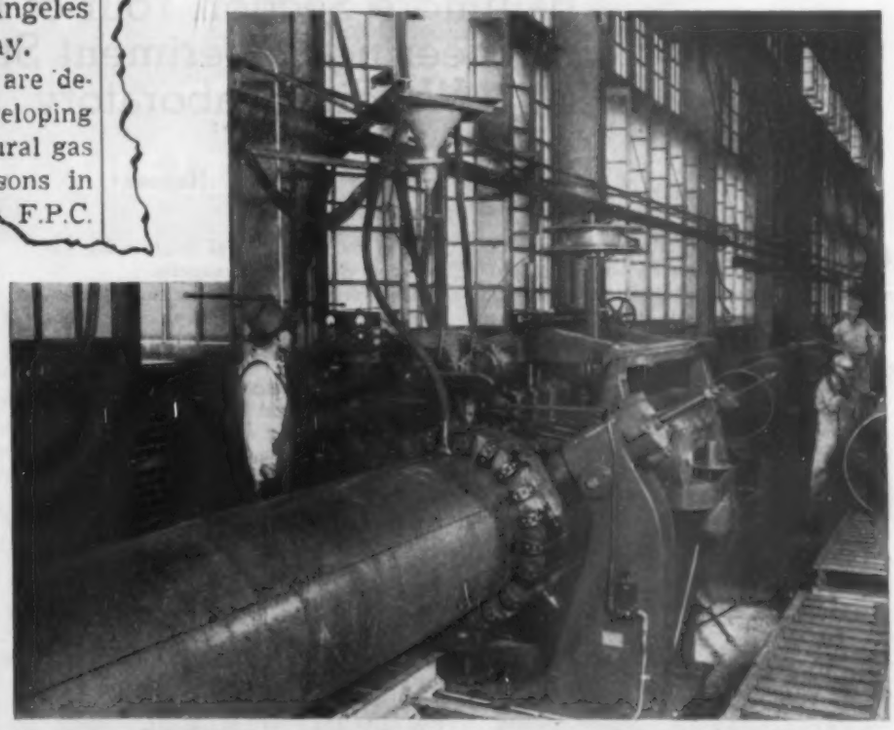
Longitudinal Seam Welders

will weld the seams of the largest pipe line ever authorized

It's a big job to weld the seams of 30" fabricated pipe. It must be done economically and the machines for doing it must be dependable—that's why the Consolidated Steel Corp. selected the 3C Berkeley for this important work. They know it will deliver uniform, high quality welds continuously day after day.

There's a size "Berkeley" to weld preformed tubes 5" to 36" in diameter.

Write us, we will suggest the best type for your requirements.



Illustrated is a Type 3C "Berkeley" in operation. Machines like this will be used for welding the pipe for this big undertaking.

PENN TOOL & MACHINE CO.

DANVILLE, ILLINOIS

List of New Members

July 1 to July 31, 1946

CHICAGO

Chmielewski, Steve (C), 5006 S. Elizabeth St., Chicago 9, Ill.
Melichar, Joseph A. (C), 5617 S. Richmond St., Chicago 29, Ill.
Neal, Gene Paul (B), 10440 Eggleston Ave., Chicago 28, Ill.
Tait, Robert E. (C), Edison General Elec. Appliance Co., 5660 W. Taylor St., Chicago, Ill.
Wolf, George M. (C), 2237 S. Kolin Ave., Chicago 23, Ill.

LEHIGH VALLEY

Powell, Russell (C), 502 Prospect Ave., Bethlehem, Pa.

LOS ANGELES

Della-Vedowa, Richard (C), 551 E. Palm Ave., Burbank, Calif.
Keeney, Bert (C), Shell Oil Co., P. O. Box 728, Wilmington, Calif.

NEW JERSEY

Strachan, Christopher (B), Madison Metal Wks., Inc., 42 Park Ave., Madison, N. J.

NEW YORK

Luane, Bent (B), All-State Welding Supply Co., Inc., 96 W. Post Rd., White Plains, N. Y.
Miller, Richard (C), 761 E. 31st St., Brooklyn 10, N. Y.

NORTHWEST

Gruenhagen, Keltus J. (B), 4111 Cedar Ave., S., Minneapolis 7, Minn.
Kaehn, H. H. (C), Gopher Welding Supply Co., 119 4th St., S. W., Rochester, Minn.

OKLAHOMA CITY

Finley, Elwood, 2333 S. W. 19th St., Oklahoma City, Okla.
Mankin, H. G. (C), National Cylinder Gas Co., 2131 Northeast 10th St., Oklahoma City 1, Okla.

PASCAGOULA

Craft, A. M. (C), 704 E. Harrison, Pascagoula, Miss.
Hewitt, C. L. (C), 507 11th St., Pascagoula, Miss.

PHILADELPHIA

Childs, John N., Jr. (C), 8113 Eastern Ave., Philadelphia 18, Pa.

PITTSBURGH

Butler, John T. (B), National Cylinder Gas Co., Davis Island Yard, McKees Rocks, Pa.

WASHINGTON

Griffin, Thomas J. (C), 2812 Texas Ave., S. E., Apt. 306, Washington, D. C.
Travis, Leslie H. (C), T5-2715, Navy Dept., Washington 25, D. C.

WESTERN MICHIGAN

David, Joseph (B), C. H. Dutton Co., Kalamazoo, Mich.
Geer, Clayton O. (C), Allen Elec. & Equip. Co., 2101 N. Pitcher St., Kalamazoo, Mich.

Members Reclassified

During Month of July

INDIANA SECTION

Eaglesfield, R. D., Jr. (from C to B), 2095 Montcalm St., Indianapolis 2, Ind.

MAHONING VALLEY SECTION

Hopper, Allen N. (from C to B), Chicago Bridge & Iron Co., Greenville, Pa.

Baltimore Section Tour of U. S. Engineering Experiment Station Welding Laboratory*

By Milton A. Hansen†

ON SATURDAY afternoon, April 6, 1946, approximately one hundred members and guests of the Baltimore Section, A.W.S., visited the Welding Laboratory of the U. S. Naval Engineering Experiment Station at Annapolis.

The Welding Laboratory furnishes information for use in Navy Department Material and General Specifications. This concerns weiding materials, equipment, welding procedures, qualification of welding, brazing, metal spray operators, and methods of testing weldments. Research activities include the development of tests to determine the weldability of steels. Engineering problems, incidental to fabrication by welding, are also investigated.

The Welding Laboratory is divided into three sections: (1) applied research investigations; (2) special research projects; (3) type approval, inspection and process approval tests.

Prearranged groups of about 25 visitors arrived at the Station during 1-hr. intervals. These were subdivided into two parties and a guide assigned to each party.

* The opinions expressed herein are the writer's and are not necessarily those of the American Bureau of Shipping.

† Surveyer, American Bureau of Shipping.

Fig. 1—Manganese Bronze Propeller in Position for Welding. Note Holes in Right Blade

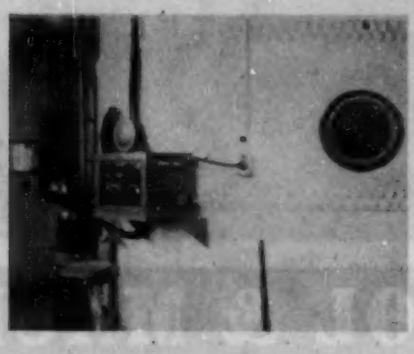


Fig. 2—Lower Section of Diving Tank, at Monitor Section

Fig. 3—Rotating and Aligning Machine

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Fig. 4—All Position Welding Machine. Note Electrode on the Right and Controls at the Left

The first exhibit showed torches used in developing procedures for welding heavy sections of manganese bronze, such as those used in propellers. An oxyacetylene process capable of welding any encountered thickness of propeller has just been completed. The setup for welding is shown in Fig. 1.

The next object of interest was a 200-kw. capacity spot welder. This has thermocouple-controlled refrigerant-cooled electrodes. The temperature control of this apparatus functions in three independent phases. It is suitable to weld air-hardening alloys and may be used in developing the welding procedure of various ferrous metals to a total thickness of $^3/_4$ in. In the same room was shown the installation of the submerged arc-welding equipment used in connection with weldability and stress studies.

Adjacent is a room containing a photoelastic device known as a polariscope. The study of joint design and the quantitative determination of various types of stress raisers is possible by the apparatus. This is employed in connection with the education of the officers in the Navy Post-Graduate School. Magnetic analysis by means of a pair of search coils, a wave trap and an oscilloscope was demonstrated. The principal stresses in a heavy-wall low-alloy steel tube of 10-in. iron pipe size was determined. The oscilloscope registered the change in the magnetic properties of the pipe. A portable X-ray defraction outfit applied to determine the surface stresses in tubing and other structures was brought to the attention of the visitors. Another apparatus of the nondestructive stress-determining type was shown. This device acts on the principle of energy absorption employing high-frequency induction at various frequencies.

The upper level of the Welding Laboratory's underwater cutting and welding diving tank is next to the instrument room. On this level the visitors saw a diver, one of the crew of three attached to the Welding Laboratory, being helped into the diving gear. He descended into the diving tank, shown in Fig. 2, filled with fresh water for better visibility. The engineer in charge of this operation is a qualified diver and supervisor of diving operations. He pointed out that in most of the test work Severn River water is used to simulate conditions encountered in service.

The demonstration showed ceramic tubular electrodes applied by the arc-oxygen method, to cut $^1/_2$-in. steel plate. In addition underwater arc welding was performed using the Navy's self-feeding technique. The arc length was governed by the thickness of the electrode covering. This is particularly successful in developing single-pass fillet welds. The procedure is employed using $^5/_{16}$- and $^7/_{32}$-in. diameter electrodes in the vertical and overhead positions. For horizontal joints $^1/_4$-in. diameter electrodes were used. The operations were clearly seen through five glass ports, set at eye level, in the diving tank.

Safety features were noted. The simple signals from diver to monitor and from monitor to diver were clearly heard through the intercommunicating telephone system.

The above exhibits were located in a building known as the Welding Laboratory Annex. A library of metals used in the Laboratory's current investigations is also housed in the Annex.

The visitors entered the main building of the Laboratory. There they were shown a 20-kw. high-frequency generator of the electronic type. This functions at an output of 400 kilocycles. A display board, mounted alongside the generator, showed the typical applications of high-frequency heating for external and internal surface hardening and silver brazing. The demonstration showed one phase of the Station's method for determining the applicable welding procedure for steels. The midportion of a $^3/_8$- x $1^1/_2$- x 8-in. steel bar was heated to 2150° F. in 49 seconds. This recreates the same metallurgical conditions as occur in the heat-affected zone of multi-pass arc welds.

The next exhibit was the hydraulic rotating and aligning machine. This motor-driven machine, shown in Fig. 3, was developed by the Station for welding propeller shafting; primarily, those fabricated as hollow forgings of the $3^1/_2$% nickel; 0.40% carbon class AN steel. The installation showed a section of a hollow forged shaft representing a completed weld being given the stress-relieved treatment. A three-part portable induction heating coil, also the Station's design, was mounted to permit free rotation of the shaft so that it may be positioned to eliminate warpage. The coil was energized from a 37.5-kw. 220/300-v. transformer. An automatically governed controller, assembled on a truck, was located alongside the shaft.

The Laboratory's thyratron-controlled, hydraulic, all-position, welding machine, as shown in Fig. 4, was operated for the visitors. This machine is used in connection with welding electrode type approval tests. It is applied to determine the current range and arc stability of low-alloy, all-position, steel welding electrodes. Approved electrodes ($^1/_8$-, $^5/_{32}$-, $^3/_{16}$-in.) were deposited in the vertical and overhead positions.

The Laboratory is equipped with direct-current variable potential generators; all approved brands are represented. There is a 750-amp. capacity set with eight welding stations and in contrast a rectifying type welding machine with 75-amp. maximum output is available for use with small electrodes. In addition there are several heavy-duty welding transformers

Fig. 5—X-Ray Room

of 300, 400 and 500 amp. capacity; also, an atomic hydrogen welding set with special devices needed for helium arc welding.

The gas-welding section of the Laboratory is equipped with oxypropane heating and melting tools together with oxyacetylene burning and welding torches. Any oxyacetylene burning machine is available for use in the research problems of the station.

On display were several types of electrical instruments intended for specific applications. The guides pointed out several meters used to determine the hot hardness of hard surface overlay alloys. These are employed as trim in steam and internal combustion engine valves. A heavy-duty alternating torsion fatigue testing machine was shown in operation. Some of the visitors looked at the Rockwell hardness tester and the Tukon mikrohardness tester. In the 20-ft. square, lead-lined X-ray room, as shown in Fig. 5, a demonstration was given. The X-ray equipment consists of a 220-kv. self-rectifying machine mounted on a jib crane. The controls are located in an adjacent room which leads into the film processing room. The principles of X-ography were briefly explained by means of color charts. Several types of defects, revealed by X-ray examination, were on display. The magnetic powder method of inspection was also shown.

The Station's oil-powder method of flaw detection was the last demonstration. This procedure employs a special processed compounded penetrating oil which seeps into crevasses, even in the presence of moisture. A very fine absorbent white powder is lightly dusted on the object. Surface defects appear as red lines sharply outlined against a dull white background. Defect indications can be photographed hours after the application of the penetrating oil by redusting the surface. Orthochromatic films must be used to obtain the desired contrast on the photograph.

Acknowledgments

The writer desires to express his appreciation for the valuable assistance and encouragement given by Bela Ronay, Principal Welding Engineer of the U. S. Naval Engineering Experiment Station. He also wishes to thank J. W. Gore, Welding Engineer of Bethlehem Steel Company, Baltimore, Md., for his help in getting the photographs included in the above paper.